A STUDY OF SOIL AERATION DURING DRAINAGE USING THE PLATINUM MICROELECTRODE TECHNIQUE

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY
Lars Erik Danfors
1960

This is to certify that the

thesis entitled

A Study of Soil Aeration During Drainage Using

the Platinum Microelectrode

presented by

Lars Erik Danfors

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Soil Science

A. Earl Erickson
Major professor

Date December 2, 1960

O-169

A STUDY OF SOIL AERATION DURING DRAINAGE USING

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By

Lars Erik Danfors

AN ABSTRACT

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Soil Science

1960

Approved by [signature]

Lars Erik Danfors

ABSTRACT

This investigation has shown that a great deal of information can be obtained regarding the effects of drainage on soil aeration by measuring the oxygen diffusion rate (ODR) in the soil with the platinum microelectrode technique. Measurements of the ODR and moisture content of the surface soil were made at five locations, four of which were in Michigan and one in northern Ohio, to study the effects of different methods and intensities of drainage on soil aeration. Laboratory experiments were also designed to study how the structure and moisture conditions of the soil system affected the ODR to the platinum electrode surface.

Tile drainage and bedding were found to increase the ODR of the surface soil in proportion to the lateral distance of the soil to the tile or bed ridge. This relationship could conceivably be used as a basis for determining the most appropriate spacing of such drainage facilities.

Over a period of time the ODR of the surface soil was found to fluctuate according to the combined effects of rainfall and drainage. The rate at which the ODR increases during drainage could also appropriately be used in facilitating better drainage designs, since it determines the period of time over which the soil will be oxygen deficient to plant roots.

Lars Erik Danfors

The ODR and corresponding moisture content during drainage of the five soils studied were found to be linearly correlated. The regression equations obtained showed that the ODR factor increased two and threefold in relation to the moisture content, clearly illustrating thereby the influence of excess moisture on soil aeration. From the ODR-moisture content relationship the optimum degree of drainage for a soil could be obtained, knowing the ODR requirements of the crop to be grown.

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11/7/61

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to:

His major professor, Dr. A. E. Erickson, for his personal interest and unfailing support throughout the author's doctorate training.

The Head of the Soil Science Department, Dr. R. L. Cook, for his kindly help in directing the author's study program.

Professors E. P. Whiteside and E. H. Kidder for their willing assistance and valuable advice.

The W. K. Kellogg Foundation for its financial support and the excellent way it has arranged and supervised the author's studies in the United States.

Michigan State University for kindly sponsoring the author's second year of study at the university through an appointment as research assistant.

His fellow students for their assistance and valuable discussions.

His wife, Birgit, for her encouragement and understanding.

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CHAPTER I

INTRODUCTION

The purpose of most drainage operations used in agriculture is to lower the water table so that excess water is removed from the soil and aeration conditions are thereby improved. The effect of lowering the water table is not only to increase the content and permeability of air in the soil, but at the same time to decrease its content and permeability to water. Thus the extent to which it is lowered must be carefully regulated in order that the requirements of the plant roots for both air and water may be fully satisfied. Knowledge of the relationship which exists between the soil air and water factor for different soils and also how these factors should be balanced throughout the growth cycle of the plant to give optimum growth, is extremely important for the design, not only of drainage systems, but of all soil management operations.

It seems at present that a great deal more is known about the water factor than is known about the air factor, both as regards the plant requirements and the soil capabilities. One important reason for this is that air is a gas and as such much more difficult to study than water. Another is that it is not a pure compound but consists of a mixture of gases, the composition of which will vary and thereby make studies of its plant and soil relations rather complicated. A third reason is that plants do not show such clear and immediate deficiency symptoms for oxygen as they do for water, which causes wilting to occur almost immediately. Under most field conditions poor aeration conditions are also of such transient and short term nature that they are easily overlooked as being important to plant growth.

Until recently there has been a very serious shortage of methods for studying and characterizing soil aeration in parameters that are of significance to plant growth. As a result of this, much of the information published on soil aeration is based on inference rather than quantitative data. In the field of drainage the lack of knowledge and of methods for measuring soil aeration is especially obvious. Thus, although the experts advocate the use of artificial drainage systems for the purpose of alleviating soil aeration, they do not base the design of these systems on actual soil aeration properties. Textbooks on land drainage, whether of applied or theoretical nature, also regretfully avoid the soil aeration aspects. Only simple "rules of thumb," based on past experience and custom are presented for the determination of the intensity of the drainage operation to be used. The rather elaborate hydraulic theory, which has been developed and generally occupies a large portion of the average textbook on drainage, is only used to calculate the dimensions of the tiles and ditches that are required to lower the water table to the degree prescribed by the "rules of thumb." This paradoxical situation illustrates rather well the great need that exists for more information regarding soil aeration and its relation to drainage and plant growth.

The purpose of the present investigation was to measure the changes that take place in the aeration properties of a soil as it drains. The platinum microelectrode technique and certain modifications thereof were used in both field and laboratory studies to characterize these changes and to more precisely explain the relationships existing between the soil air and water factor.

CHAPTER II

REVIEW OF OUR KNOWLEDGE OF SOIL AERATION AND ITS RELATION TO DRAINAGE

A. Principles of Land Drainage

Although the art of drainage was probably developed at the same time as that of agriculture, the theory of it did not develop until after Darcy published his work on liquid flow through porous media in 1856. Since then the theory of drainage has been mainly concerned with describing the movement of the ground water in the soil and how it is affected by various methods of drainage. Techniques involving mathematical analyses, sand tank models, electrical analogues and piezometers, etc., have been used to arrive at solutions to various drainage problems, Jacob 1946, Yearbook of Agriculture 1955.

The first mathematical solution to the tile drainage problem was reported by Vedernikov 1939. This and later work, especially by Kirkham and his associates, have made possible a sound mathematical explanation of the basic effects of tile drainage, which was earlier rather poorly understood, Kirkham 1957, van Schiltgaarde et al. 1956. Other drainage problems have similarly been solved thereby contributing to our knowledge of these phenomena. For practical applications, the

theoretical work has, however, been of little use, since it is based on assumptions of certain ideal soil conditions which differ considerably from those generally found in the field. Thus, because of the complexity of the soil and the natural conditions under which land drainage takes place, it has not as yet been possible to incorporate this theoretical knowledge into specific design procedures for use in the field. The judgment and experience of the drainage engineer together with certain field data which he is able to collect, still form the most reliable basis we have for making drainage designs, Luthin 1957, Frevert et al. 1955.

Simultaneously with the theoretical development of drainage there has also been great improvements made on the practical aspects. Thus, new designs, materials and methods of installing artificial drainage have been developed, Luthin 1957. Experiments have also been carried out to determine the interrelationships existing between drainage intensities, soil properties and plant growth, so that there is now a better understanding of these factors and how they are modified by local field conditions, Stolp and Westerhof 1954, Wesseling et al. 1957, Russell 1959.

In general, the results of most drainage studies have been expressed on the basis of the effects observed on the depth of the ground water table in the soil. The purpose of drainage is often also expressed in terms of the depth of the water table. Thus it is considered that the optimum depth to which the water table should be lowered by drainage essentially lies between two limits—an upper limit governed by the aeration requirements of the plant roots, and

a lower limit governed by their water requirements. Because of the difficulties involved in measuring the air requirements of the plant roots and aeration properties of the soil, efforts have been mainly concentrated on finding the lower limit. In other words far more is known at present about the minimum water requirements of plants and the availability of water in the soil than is known about the equivalent air relationships. Knowledge of the upper limit for the optimum water table depth is therefore very obscure, Wesseling et al. 1957.

The above discussion has shown that the main concept underlying both the theoretical and practical aspects of drainage is that of "water table depth." Although this concept may be of value from an engineering point of view, one may very seriously question its value as a basis for studying plant-soil relationships to drainage. Under most field conditions it is also extremely difficult to define the exact shape and depth of the water table and especially to relate this property to the water and air conditions of the root zone of the soil, which are of importance to plant growth. Thus for field research purposes it would be better if some other properties of the soil system could be found, that would more directly characterize the effects of drainage and express these in terms that are of significance to plant growth. One important possibility in this respect is to measure the flow rates of water and oxygen to the plant roots, since both of these will be affected by drainage and will also determine the suitability of the soil as a plant root environment. At present there is a method available for measuring the oxygen diffusion rate in soils, see Lemon and Erickson 1955, while methods for determining water flow are under development, see Gardner 1960 and Russell and Woolley 1960.

B. Principles of Soil Aeration

In the monograph on "Drainage of Agricultural Lands" published by the American Society of Agronomy in 1957, several of the contributors point out the very serious lack of knowledge that exists regarding the effects of drainage on soil aeration and plant growth. In the previous section it was also shown how the theoretical aspects of drainage have been developed entirely from considerations of the removal of excess water from the soil and lowering of the water table. Since, however, the primary reason for drainage is to improve soil aeration, more effort must conceivably be made to study this aspect of drainage.

A good review of the importance of soil aeration to plant growth has been given by Russell 1952. Adequate soil aeration is required not only for the growth and development of the plant roots, but also for their salt and water uptake, which governs the growth of the whole plant. The adverse effects on plant growth of excessively high moisture contents in the soil have been discussed by van't Woudt and Hagan 1957 and Russell 1959.

Soil aeration is a diffusion process by which oxygen that is used in the soil by plant roots and microorganisms is replenished from the atmosphere. It can be thought of as being composed of two phases, one consisting of diffusion of oxygen through the gas-filled pores of the soil and the other consisting of diffusion through the moisture films surrounding the plant roots. The first phase governs the movement of oxygen over fairly long distances in the soil and accounts for the supply of oxygen from the atmosphere to the root zone. It can be measured and studied by using the techniques developed by Hutchins 1926, Raney 1949 and Lemon 1952. The second phase of the aeration process is located within the root zone and is active over rather short ranges around the plant roots. It involves the diffusion of oxygen from the air-filled pores of the root zone through the moisture film to the surface of the plant root. A measure of the diffusion rate through the moisture film of a root can be obtained by using the platinum microelectrode technique developed by Lemon and Erickson 1952.

Both phases of aeration will be affected by the soil moisture content. Thus as water is removed from the soil by drainage, the volume of air-filled pores in the soil will increase as the thickness of the moisture films around the plant roots decreases. The diffusion rates of both phases of aeration will therefore increase due to drainage. The moisture content at which aeration will be optimum will be reached when the rate of oxygen diffusion due to the first phase just balances the rate of removal by the second phase. To find this moisture content, it is necessary to know not only the oxygen requirements of the roots in the root zone, but also their depth and the cross-sectional area of the soil that contains these roots. By measuring gaseous diffusion through a sample of this soil under various moisture contents using the techniques mentioned above for each of the aeration phases, it should be possible to characterize the soil conditions sufficiently well to arrive at the optimum moisture content.

For the purpose of more conveniently discussing the literature on soil aeration, the two phases of aeration mentioned above will be treated separately in the following review. It must be remembered, however, that they are very closely integrated and therefore must be considered together whenever the over-all aeration properties of a soil are defined.

1. Oxygen Diffusion Through the Gas-filled Pores of the Soil

Buckingham 1904 was the first to give definite information as to the rate at which gases move in soils and to point out some of the general mechanisms involved. He showed that air movement was caused in the soil by both mass and diffusive flow, but that the latter was by far the more predominant. Most other investigators after Buckingham also seem convinced that oxygen is supplied to the soil mainly by diffusion and that mass flow of oxygen is negligible, see Romell 1922, Penman 1940, Taylor 1949 and van Bavel 1951. In studying the diffusion of CO_2 and air through layers of various soils at different moisture contents and degrees of compaction, Buckingham was able to show that a relationship existed between the square of the air-filled pore space and the diffusion rate. He expressed this with the equation:

$$D = k\ S^2 \qquad (1)$$

where D is the diffusion coefficient and is a measure of the volume of gas in cc which passes through a soil of 1 cm^2 cross-sectional area and 1 cm thickness in one second when the partial pressure gradient of

the gas is 1 mm Hg per cm. The symbol k is a proportionality constant and S is the fraction of air-filled pores per unit volume of soil. For gaseous media S = 1.0 and therefore D = k, meaning that k actually represents the diffusion coefficient for gas (oxygen or carbon dioxide) diffusing freely through air. Buckingham's equation can therefore be rewritten as:

$$D/D_o = S^2 \qquad (2)$$

where D is the coefficient of diffusion through a soil of pore space S and D_o is the coefficient of diffusion through free air (S = 1.0). This equation states that the diffusion of a gas through a soil is proportional only to the square of the air-filled porosity S and is independent of the moisture content of the soil except as far as this affects S. It was quite some time after Buckingham's work before any further contributions were made to the problem of gas diffusion in soils. Penman 1940 was probably the first to elaborate on Buckingham's work. He introduced corrections for the reduced cross-sectional area available for the movement of gases in the soil and also for the increased length of path, which the gas molecules must follow in the soil as compared with free diffusion in gaseous media, due to the tortuous nature of the soil pores. He also found that diffusion through the soil varied not as the second power of the air-filled pore space S, but as the first power. His equation can thus be written:

$$D/D_o = k\ S \qquad (3)$$

Penman showed that the proportionality constant k is related to the path length L_e taken by the gas molecules in moving through the soil and that in fact $k = L/L_e$, whereas L is the length of the soil column studied. He reasoned on the basis of work done by Carman 1939 on viscous flow of liquids through soils, that the gas moves through the soil as though it makes an angle of 45° with the direction of the soil column (direction of maximum pressure gradient). That is L/L_e is approximately $1/\sqrt{2}$, and the diffusion equation becomes:

$$D/D_o = S/\sqrt{2}$$

Penman used carbon disulfide and acetone vapors as well as CO_2 gas for his diffusion studies. He made measurements of the diffusion through various porous media including natural soils at different moisture contents. His experimental data showed that within certain limits of S $(0.0 < S < 0.6)$

$$D/D_o = 0.66\ S \qquad (4)$$

for steady state conditions, and that D/D_o was dependent only on the air-filled porosity S, being independent of the nature of the solid, its moisture content or texture except as far as these affected S. The difference between the theoretically derived value for k of $1/\sqrt{2}$ or 0.7 and the experimentally obtained value of 0.66 was close enough to support the theory.

Millington 1959, however, is of the belief that in flow theory for porous media, the concept of spatial distribution of pores cannot be neglected as Penman has done. Assuming the pores to be approximate spheres, and knowing roughly the number of each size of pores existing per unit volume of soil, Millington shows that it is possible to correct Penman's equation for the "structure" of the pores, and arrives at a value for $k = S^{1/3}$, so that Penman's equation becomes modified to:

$$D/D_o = S^{4/3} \tag{5}$$

for steady state diffusive flow in dry porous solids. This treatment endows k with characteristics of length and makes it an index of the number of pores per unit length. For gas diffusion in wet porous solids the total air-filled porosity S should be replaced by the effective air-filled porosity S_e which Millington suggests can be computed by knowing the number *n* of pore classes drained from the total number *m* of equal-volume porosity components in the soil. Thus the true theoretical relationship for gas diffusion in porous solid-liquid-gas systems becomes:

$$D/D_o = n^2(S_c^{4/3}/m^2) \tag{6}$$

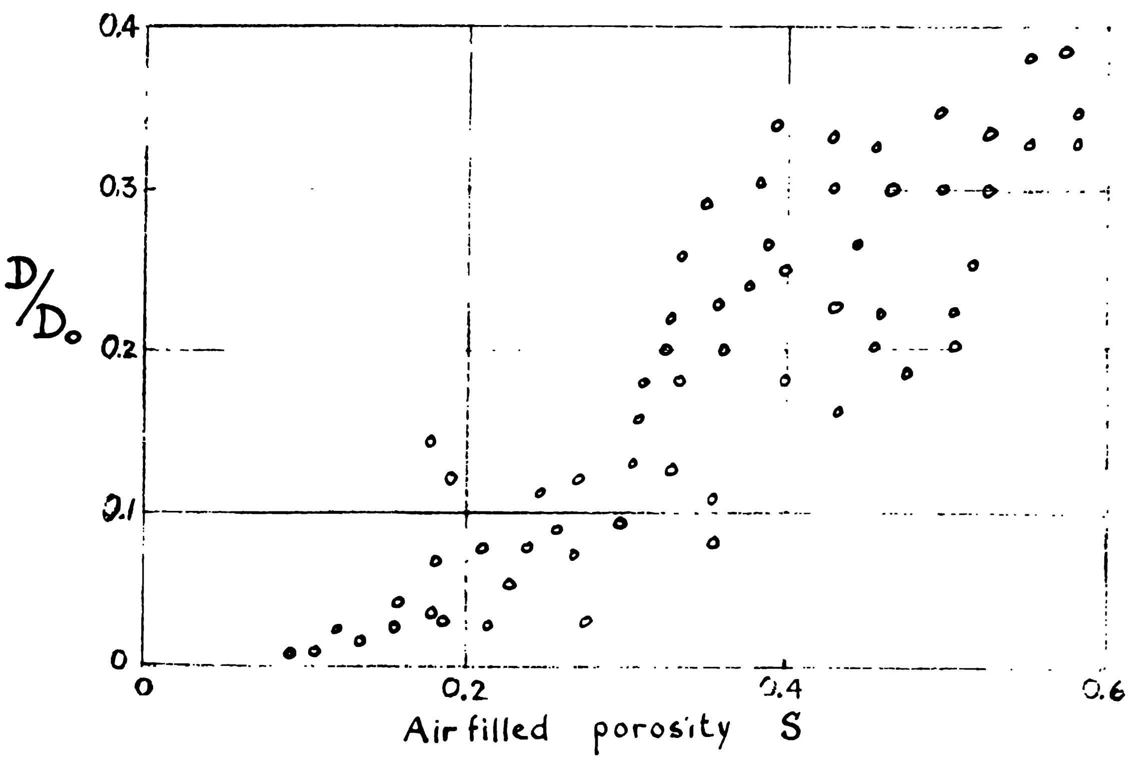
The curvilinear relationship obtained in equations (5) and (6) is due to the nature of the change in probability of continuity of pores in the dry and wet condition of the porous media. Using the experimental data presented by Penman and several other workers, Millington showed how much better his equations fitted the data than the linear functions previously used.

Taylor 1949 in attempting to find a suitable parameter for characterizing soil aeration wrote the diffusion equation as:

$$D/D_o = 1/\lambda^2 \tag{7}$$

where λ is called the "Equivalent Diffusion Distance" and has units of length. It is measured in such a way as to represent a tube of unit cross-sectional area and of such a length that free diffusion through this tube is exactly equivalent to the diffusion that takes place in the soil. When he calculated values for k from Penman's equation (3) Taylor found they varied according to the soil he used, and that only one of them gave a k value which approached the 0.66 received by Penman. The same criticism that was made by Millington has also been made by Blake and Page 1948, who studied diffusion of carbon disulfide vapor in various soils under field conditions. In relating D/D_o with air-filled porosity S they found values for k ranging from 0.7 to 1.3. These results were attributed to the fact that the field soils which they studied had a much more heterogeneous system of pores than the prepared samples with which Penman had worked. Therefore, they concluded that the nature of the air-filled pore space would influence the diffusion much more than was previously supposed. In future work on diffusion it seems that the nature and structure of the pores as well as the total air-filled porosity must be taken into account.

Blake and Page also found that when S, the air-filled pore space, dropped below 0.10 to 0.12 the diffusion of vapor was essentially stopped. In other words diffusion approaches zero before zero porosity is reached, especially for moist soils. It seems that Buckingham's data indicate the same thing although he did not state this. Thus an extra-polation to zero diffusion occurs for his data at S equal to 0.15 (that is 15% air porosity). The results received by many other workers also support these findings (see Wesseling et al. 1957). If the values of D/D_0 from various sources are plotted in a graph against the corresponding porosities S, the figure shown opposite is obtained. This also indicates how zero diffusion occurs around S = 0.10, which must constitute pore spaces that are blocked and are non-functional in gaseous diffusion.



Data taken from Buckingham 1904, Penman 1940, Taylor 1949 and van Bavel 1952 (plotted by Wesseling et al. 1957).

Van Bavel 1951 has probably gone furthest in the mathematical treatment of the aeration process in soils, in that he has even taken into account the rate at which gases are consumed or liberated in the soil, referred to by him as the "activity" of the soil. His general expression may be written:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{D}\left(\frac{\partial p}{\partial t} - \beta \alpha\right) \tag{8}$$

where p = partial pressure of the gas in mm. Hg.

x = depth in cm.

β = ratio of partial pressure and mass increments of the gaseous phase. That is $\beta = \frac{\partial p}{\partial m}$ per unit volume.

α = activity per unit volume of soil. It is the amount of medium of gas in mg./cm.^{3}/sec. which is formed per unit of time in the soil. For absorption of gas it is negative in sign.

t = time in seconds.

D = diffusivity of the gas under consideration into air in the porous medium as it exists. It is equivalent to Penman's D/S. In the equation D is assumed to be constant for the soil chosen, but in reality it depends on the concentration of water and air in the soil.

By solving this partial differential equation for various initial and boundary conditions, van Bavel was able to obtain formulae, which gave the partial pressure p of a gas at any point in the soil, whether this gas was being generated or consumed there. Also by defining all units on the basis of the medium as a whole rather than on the gas phase alone, the diffusivity D of the gas through the soil became dependent only on the nature and state of the gas and not on the soil characteristics. Actually the diffusivity is determined by the ratio between the mass and partial pressure changes of the gas. The air-filled porosity of the soil will therefore affect the diffusivity by changing the mass of gas present per unit volume of soil. For diffusion in the steady state, equation (8) can be simplified to:

$$\frac{\partial^2 p}{\partial x^2} = -\beta/D \ \alpha \tag{9}$$

which is a form of Poisson's equation and more clearly shows how the deficit or excess of the partial pressure of a gas in the soil over that in the atmosphere is directly proportional to the biological activity α of the soil and inversely proportional to the "specific diffusion impedence," β/D, which is a characteristic of the medium. The partial pressure is also dependent on the depth being studied as well as the total depth of the "active" soil. From van Bavel's equations and from a knowledge of the nature and state of the gas and soil being studied, it is possible to calculate the distribution of the gas with depth in the soil, see Wesseling et al. 1957.

Several workers have developed methods for studying the oxygen diffusion rates in soils under field conditions, Hutchins 1926, Raney 1949, Lemon 1952. These have been based mainly on measuring the rate of diffusion of oxygen into an oxygen-free chamber buried in the soil. Most of these chambers have been equipped so that they can be left in position in the soil for continuous measurements. Before each measurement they are flushed with nitrogen gas to remove all the oxygen, after which the ports leading to the surrounding soil are opened for a known period of time, so that there can be a gaseous exchange between the chamber and soil. The chamber is then closed and the oxygen content of the enclosed gas is determined. The change in oxygen content during the diffusion period or the ratio between the diffusibility of oxygen in the soil D as compared with that in air D_0 is then used as a measure of the rate at which oxygen can be transmitted in the soil.

The main criticism of these methods is that the volume and cross-sectional area of soil involved in the diffusion process cannot be determined. Furthermore the determination of the values of D, the diffusivity of oxygen in the medium, is based on the assumption that the diffusion process is linear in nature, which is generally not the case for these methods. Measurements must also be made of the concentration of oxygen in the soil air before the diffusion rate is measured, since it will determine the oxygen concentration gradient established between the soil and the chamber and therefore be one of the main factors affecting the diffusion rate. An accurate measure of the oxygen concentration of the soil air around the diffusion chamber is difficult to determine. Due to contamination from atmospheric air when the chamber is installed it may also be changed considerably from that in the soil proper.

2. Oxygen Diffusion Through the Moisture Film Surrounding the Plant Root

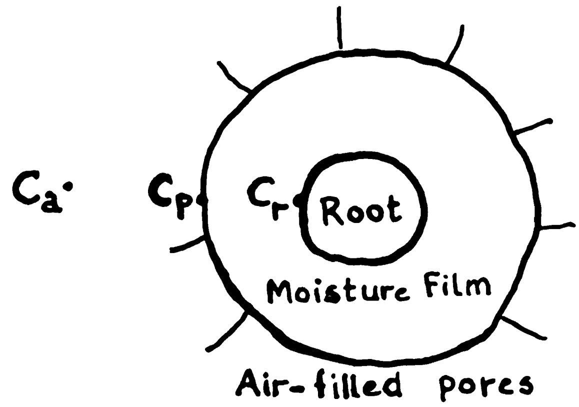
The electric analog method so commonly used for solving water flow problems in drainage studies can also be utilized for facilitating a better understanding of the soil aeration process which occurs through the moisture film surrounding plant roots. Thus the rate at which oxygen moves from the air-filled pores of the soil through the moisture film to the plant root surface can be compared with the electric current that is supplied from a battery to an external circuit. Both of these processes will in their degree of performance depend on three main factors. These are:

a. The Capacity Factor Q which represents the total amount of oxygen Q which exists around the root at any given time. Oxygen will occur in the soil in both the air and water phases, but since the content is very low in the water phase, this can for practical purposes be neglected and only the content in the air phase be considered

$$\text{Thus} \qquad Q = C_a V_a \tag{10}$$

where V_a is the total volume of air-filled pores and C_a is the oxygen concentration of the air in these pores. The capacity of the soil for oxygen is equivalent to the total electric charge of the battery, which is equal to the product of the area of the electrodes times their charge density.

b. The Intensity Factor C represents the concentration (or partial pressure) of oxygen at any point in the soil medium. Since the plant root is surrounded by a water film outside of which there are air-filled pores, it may be convenient to differ between three different intensities of oxygen in the soil medium.



Thus C_a = oxygen concentration in the air-filled pores.

C_p = oxygen concentration in the moisture film at the air-water interface of the surrounding pores.

C_r = oxygen concentration in the moisture film at the root surface.

The oxygen intensity factor C at any point in the soil is equivalent to the electrical potential E of the battery at any point in its circuit.

c. <u>The Rate Factor F</u> is a measure of the rate at which the soil medium is able to supply oxygen to the root. It will depend on the difference in intensity of oxygen in the soil and at the root surface. Since the oxygen diffusion rate in the air phase of the soil is of the order of 10^4 times faster than in the liquid phase (moisture film) it can be assumed that the concentration or intensity of oxygen at the air-water interfase of the moisture film surrounding the plant root C_p is always maintained in equilibrium with that of the air-filled pores C_a. The rate of flow of oxygen F to the plant root across the moisture film will then be directly proportional to the difference in oxygen intensity at the air-water interface C_p and the root surface C_r

$$F = k(C_p - C_r) \tag{11}$$

where k is a proportionality factor that is dependent on the nature of the medium across which the oxygen is transmitted. Since oxygen moves by diffusion from the air-water interfase of the water film surrounding the root to its surface, k is a measure of the diffusibility of oxygen in the film and can be written:

$$k = D \frac{A}{L} \tag{12}$$

where A is the surface area of the root.

L is the thickness of the water film.

D is the diffusion coefficient of oxygen in the water film.

Substituting equation (12) into (11)

$$F = DA \frac{(C_p - C_r)}{L} \tag{13}$$

which is identical with Fick's first law of diffusion, where $\frac{(C_p - C_r)}{L}$ is the concentration gradient between the root and the soil medium. It will be noticed that the flow of oxygen F will be inversely proportional to the thickness of the moisture film L. Equation (13) only holds for linear diffusion and must be changed if it is to apply to flow occurring towards a cylindrical root (radial diffusion). This condition is treated in the introduction to the laboratory studies.

The capacity factor Q will determine how long the soil is able to maintain the concentration gradient $\frac{(C_p - C_r)}{L}$, or in other words how long oxygen can be supplied to the air-water interface of the moisture film so that its concentration of oxygen will remain at the initial C_p. As soon as C_p decreases, the flow F will also decrease.

In the case of the battery the rate factor is equal to the electric current I which the battery can supply to a given external circuit and will depend on difference in electrical potential between the ends of the circuit $(E_2 - E_1)$. Thus for the battery

$$I = k(E_2 - E_1) \tag{14}$$

where k in this case is found to be equal to the reciprocal of the resistance R of the circuit. Then

$$I = \frac{(E_2 - E_1)}{R} \tag{15}$$

which is Ohm's law and is equivalent to equation (13) above.

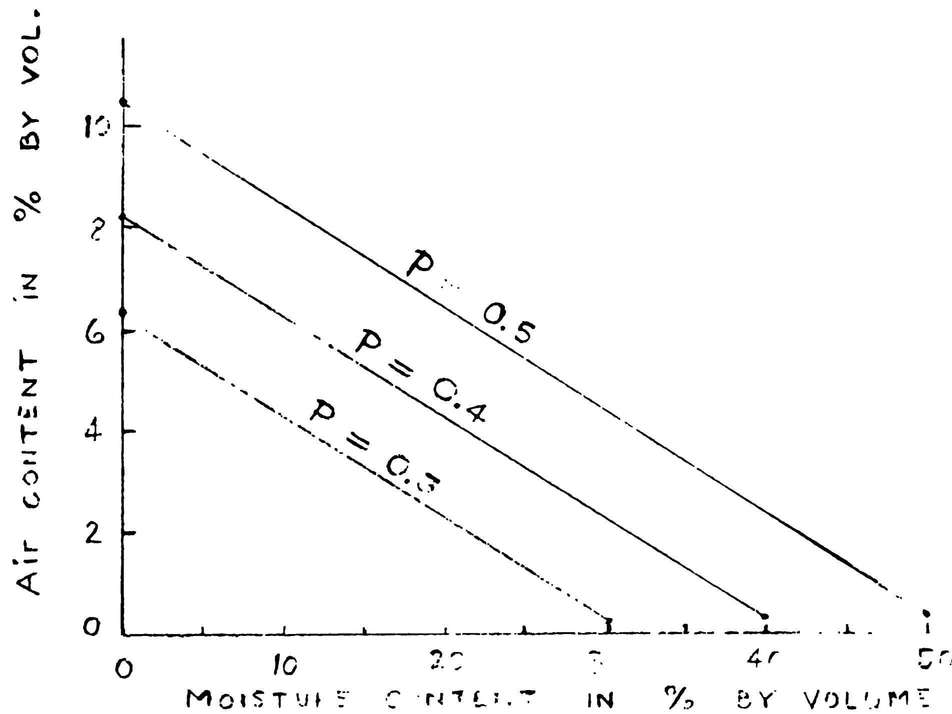
Now the analogy made above between the soil and the battery will only hold if certain restrictions are placed on the soil. Under natural conditions the soil, unlike the battery, which essentially functions under the same physical conditions at all times, will constantly be undergoing changes through the influence of external forces. Thus microorganisms and plant roots other than the particular root being studied will deplete the oxygen contained in the soil medium, thereby affecting all three of the factors discussed above. The soil moisture conditions of the soil will also be constantly changing through the action of weather, drainage, and plant activity. In other words the soil system is a much more dynamic and complex system than that of the battery and for purposes of study must be broken down into a series of composite structures where conditions are simpler and the effects of individual factors can better be evaluated.

In the literature review which follows, an attempt has been made to discuss each of the aeration factors mentioned above and to categorize the work reported according to these factors. Since the purpose of this investigation is to study how drainage (removal of excess water) affects the over-all aeration properties of the soil, special attention will be given to the manner in which soil moisture has been found to affect these aeration factors. Finally their effects on plant growth and the methods by which they are characterized will be discussed.

3. The Capacity Factor

This factor represents the total amount of oxygen which a soil contains at any given time. Since oxygen exists in both the gaseous and liquid phases of the soil, its magnitude will also depend on the relative amounts of both of these phases in the soil. If it is assumed that the concentration of oxygen in the soil air is 21% by volume, and that in the soil water it is 0.7% by volume (i.e. equivalent to the content of air saturated water at 15°C), it is easy to calculate the amount of oxygen that a soil will contain for any given porosity and moisture content. This is assuming there is no biological or chemical activity existing in the soil to deplete the oxygen concentration in either of these phases. In fact, if certain porosities are assumed (0.3, 0.4, and 0.5) and for each of these the complete moisture scale is considered from the dry to the saturated state, straight line relationships such as those shown in

the figure below will be obtained.



This figure relates the volume percent of oxygen contained in both the water and air phases of the soil with the corresponding moisture content of the soil. As can be seen, the oxygen content of the soil is almost entirely governed by the volume of air-filled pores it contains. Thus when the soil is saturated with water, it will only contain about one-half a volume percent of oxygen irrespective of the porosity of the soil (i.e., within the limits generally found in soils). If, however, 10 volume percent of water is drained from the soil and replaced by air, a five-fold increase in oxygen content will result. This demonstrates rather nicely the large changes which occur in oxygen content as rather small changes in moisture content occur. In other words there is a strong inverse relationship between the soil air and moisture contents.

Besides total porosity, the structure of the pore system is found to be very important in determining the air content of a soil under various field conditions. Thus drainage always takes place in the largest pores first. A very clear and detailed description of how the geometry of the pore space of an "ideal" soil affects the distribution of water and air has been given by Keen 1931 in his review of the work done by Haines and Fischer. Haines used a very simple "soil" system composed of equal sized glass beads arranged in closest packing so that he could define mathematically the geometry of the system and the distribution of the water and air phases therein. With this approach he was also successful in demonstrating and explaining several phenomena, about which there was earlier some misunderstanding (e.g., the "hysteresis effect").

Schumacher 1864 recognized the importance of the geometry of the pore spaces of natural soils and introduced the idea of separating these into capillary and non-capillary pores. The non-capillary pores were those that were drained under field conditions and the capillary pores were all the others which after drainage remained full of water. With the same ideas in mind Kopecky 1927 introduced the term, air capacity, to define the total volume of the non-capillary pores, which he found were of the greatest importance for the aeration of the soil.

Kopecky also determined the air capacity requirements for optimum growth of many of the cultivated plants and arrived at values between 10 and 30 per cent of the total soil volume. Baver and Farnsworth 1940 showed in experiments with sugar beets that both the early stand of the beets as well as the total yield of beets were

related to the non-capillary porosity (air capacity) of the soil. Thus a loss in the stand of beets was found for a non-capillary porosity less than 16% and a loss in the final yield of the beets was obtained when this porosity dropped below 10%. Several other workers have used the same concept of non-capillary porosity of air capacity, to characterize soil aeration and plant requirements. Payne 1952 has given a good summary of these results and showed how various crops differ in their requirements. Wesseling and Wijk 1957 demonstrate the way in which these values may be used to estimate the most appropriate depth of the water table (or tile line) so that adequate aeration conditions can be provided in the root zone of the soil.

In general the reason why the non-capillary porosity of the soil has been found to be of such importance to plants is not so much that they especially require large volumes of air around them or that the diffusion of oxygen is so much better through the large pores than through the smaller ones, but mainly because they determine the permeability of the soil to water and are the first passageways to be air-filled when the soil has drained. Thus the removal of excess water from the surface of the soil by infiltration and from the sub-surface portions of the soil by drainage is mainly governed by the volume of the non-capillary pores. The magnitude of the non-capillary porosity will therefore determine the length of time required to remove excess water from the soil and thereby to relieve it of poor aeration conditions. Since most plant roots can tolerate only very short periods of oxygen deficiency, the significance of the non-capillary porosity becomes rather apparent.

Although the determination of total volume of non-capillary pores is a useful criterion for characterizing soil aeration, it has its limitations because of the dynamic nature of this property. Thus as discussed by Baver 1956, the non-capillary porosity will be affected by a number of different factors such as the texture and humus content of the soil, tillage operations, compaction processes, wetting and drying, etc. In this connection Haines 1923 has developed an interesting picture of the changes in soil structure caused by volume changes associated with varying moisture content. He found that as a water-saturated soil was dried, a decrease in volume of the soil occurred at first, which was equal to the volume of water lost. Because of this volume change cracks were developed, the nature of which depended on the mineralogical and textural composition of the soil. After drying had proceeded for a time, a point was reached when the shrinkage in volume became less than the volume of water removed and at this stage air began to enter the finer pores of the soil mass itself. This process is illustrated in Figure 1, where two consecutive photographs of a Brookston loam soil show the large cracks which developed as the soil dried out. It should be pointed out, that although the non-capillary porosity of a partially dehydrated soil may on the whole increase due to the establishment of large cracks, the corresponding porosity for the soil mass in between the cracks will generally decrease. In other words there is, from an aeration point of view, generally a degradation of the pore structure in the aggregates formed between the cracks rather than an improvement, as might be expected, when water is removed. This can also give rise to situations where

Soil in the saturated condition

Soil in a semi-dry state

Figure 1. Photographs of the surface of a Brookston loam soil taken at Station I, Soil Science Farm, showing the shrinkage and development of cracks due to drying.

both aerobic (situated near the cracks) and anerobic conditions (situated within the aggregates) prevail simultaneously in the soil.

The methods used to measure the air and water volume of soils have been described by Russell 1949. A known volume of soil is generally sampled and gravimetrically measured for its moisture content and also bulk density. From these values it is possible to fairly accurately determine the relative volumes of the solid, liquid and gaseous phases which the soil contains. The relative volumes may also be determined by use of an air pycnometer method, whereby the volumes of each phase is obtained by use of the ideal gas law.

4. The Intensity Factor

The intensity or concentration of oxygen in the soil at any given time will depend on the difference between the rate at which it is utilized by the biological reactions occurring in the soil and the rate at which it is replenished by the gaseous exchange occurring between the soil and the atmosphere. The biological reactions which account for the use of the oxygen in the soil, consist partly of the respiration of higher plant roots and partly of the aerobic decomposition of organic material by microorganisms. The net result of both of these is the same in that they both oxidize carbon compounds to carbon dioxide.

It is quite evident that measurements of the composition of the soil air will furnish information not only of the oxygen status of the soil, but also of the relative effects of the biological and gas-exchange processes occurring therein. For this reason the oxygen content of the soil has also been found to be a valuable parameter with which to characterize soil aeration properties. Factors such as soil moisture content, structure, temperature, etc., which affect these processes can also be evaluated to a relative degree by measuring the changes which occur in the soil air composition.

Most of the investigations made on the intensity of oxygen in the soil have been concerned with conditions in the gas phase and very little indeed has been done on the oxygen concentration of the liquid phase of soil. Runkels et al. 1958 have reported some interesting work on the sorption of oxygen by both the liquid and solid phases of the soil. They found that the soil water dissolved less oxygen than the theoretical amount for free water and that as the moisture content decreased towards the dry state, the solid particles and especially the clay fraction sorbed considerable amounts of oxygen at their surface. Runkels 1952 also reported studies on dissolved oxygen in soils, where he passed nitrogen gas through moist soils and measured the amount of oxygen removed. He found that for a sand sample most of the dissolved oxygen in the soil water was removed within 2 minutes, while if nitrogen was passed over the surface of an equivalent air saturated water mass it took several hours to remove all the oxygen from this. He attributed this difference to the large difference in area of the gas-liquid interfase of the two medias. The exchange of gases between the liquid and gaseous phase of the soil is therefore very rapid due to the large contact area between these phases.

Measurements of the composition of the soil air belong to the oldest techniques used in soil aeration studies. Thus already in 1853 Boussingault and Lewy reported measurements of the concentration of carbon dioxide in soil air samples. Since then much work has been done on measuring the soil air composition and its fluctuations, Russell 1952 and Baver 1956. The general findings can be summarized as follows:

1) The sum of the carbon dioxide and oxygen concentrations in the soil air remains essentially the same as that in the atmosphere (i.e., 21.0%).

2) The oxygen concentration decreases with depth in the soil at the same time as the carbon dioxide content increases, Boynton and Reuther 1939, Raney 1949, Wiegand and Lemon 1958.

3) Rainfall and irrigation which cause an increase in soil moisture content generally cause simultaneous reductions in the oxygen concentration, Wollny 1886, Furr and Aldrich 1943, Boynton and Reuther 1938, Wiegand and Lemon 1958.

4) The O_2 and CO_2 concentrations of the soil air are strongly influenced by temperature, Romell 1922, Russell and Appleyard 1915, Boynton and Reuther 1938, 1939.

5) The soil air composition will depend on the biological activity and any factors which affect it. Thus temperature, moisture, humus, etc., will all affect the biological activity and the production of CO_2, Romell 1922, Epstein and Kohnke 1957.

Besides studies on how the oxygen concentration varies in soils for different conditions, much work has also been done in trying to find the minimum oxygen concentration requirements of plants. Thus Cannon and Free 1925 studied the growth rate of roots at fixed temperatures and varying concentrations of oxygen. They tried to establish the "critical" oxygen concentration below which growth was stopped, but found it varied considerably with temperature and the type of plant studied. They also came to the conclusion that the rate of supply rather than the concentration of oxygen was a more important factor governing growth. Since a further study of the literature in this field showed that the work done is extremely heterogeneous in scope and almost impossible to satisfactorily compare, an effort will not be made to review this work here, Berry 1949, Berry and Norris 1949, Machlis 1944, Wanner 1945. In general it seems that workers in this field have too much emphasized the importance of the composition of the gaseous medium surrounding plant roots without sufficiently considering the other factors also involved in the rate of supply of oxygen to the roots.

Methods used for determining the composition of soil air have been discussed by Russell 1949. They consist of various techniques for extracting representative gas samples from the soil and analyzing these. Generally small-bore metal tubes or gas chambers are buried in the soil to the desired depth, gas samples then being drawn from these. The content of CO_2 and O_2 contained in the gas samples are determined by various standard gas analysis methods, which are usually based on absorption techniques. For determining the oxygen content, methods based on the paramagnetic properties of oxygen or its electrochemical reduction (polarographic methods) have been found to be very convenient, Carritt and Kanwisher 1959 and Hobbs 1960.

Although the gas sampling methods used for characterizing soil aeration are very worthwhile, they have certain disadvantages which limit their validity and use. Thus when a gas sample is taken it is generally very difficult to prevent some contamination from the atmospheric air. Generally it is also impossible to determine the exact depth or position from which the samples came or on a quantitative basis to define the exact volume of soil from which they were removed.

Soil aeration has also been characterized by measuring certain physico-chemical properties which are thought to be dependent on the aeration status of the soil. Most of these are actually expressions for the average value of the intensity factor. Thus Vine et al. 1942, Hardy 1943, Hoffer 1945 and Lemon 1948 measured the degree of oxidation or reduction of iron and/or manganese as a method for characterizing the aeration conditions of the soil. Bradfield et al. 1934, Peech et al. 1935 and 1937, Starkey et al. 1945, Quispel 1947, McKenzie and Erickson 1954 measured the redox potential and Lund 1928, Groh 1926, Marsh 1935, Burr 1945 and Lemon 1952 have tried methods for measuring the bio-electric potential, which is the electrical potential developed between the plant root and its growth medium.

Unfortunately troubles arise with all these methods in that they are not solely dependent on the aeration status of the soil, but also on a large number of other environmental factors. For the short periods that are of interest to the plant scientist, the soil is also too well poised to register any measurable differences in the oxidation-reduction status due to various treatments affecting the aeration conditions of the soil. These methods are therefore better suited for studies of soil genesis, where longer periods of time are involved.

5. The Rate Factor

The platinum microelectrode technique developed by Lemon and Erickson 1952 measures the oxygen diffusion rate from the air-filled pores in the soil through the moisture films to the surface of the electrode, in much the same way as plant roots would experience it under the same soil conditions. This technique therefore gives a direct measure of the rate factor.

The apparatus consists of a platinum wire electrode which can be inserted in the soil to any desired depth for in situ measurements of the oxygen diffusion rate. By maintaining the electrode at a negative electric potential relative to the soil, oxygen which occurs at its surface is electrolytically reduced and thereby removed in much the same way as oxygen is removed from a similar sized plant root by respiration. Because oxygen is removed from the electrode surface a concentration gradient is established, which causes more oxygen to diffuse to it from the surrounding soil medium. The rate at which oxygen diffuses to the electrode and is reduced there, will determine the magnitude of the electric current flowing through the circuit of the electrode apparatus. Thus by recording the electric current which flows through the electrode system, the oxygen diffusion rate to the electrode from the surrounding soil can be determined. The value of the electric current will depend not only on the oxygen concentration gradient set up between the electrode and the medium, but also on the moisture and structure conditions of the soil.

Much work has already been done to apply the microelectrode technique for soil aeration studies under various conditions. Van Doren 1955 and 1957 has developed an apparatus suitable for field measurements, see Figure 2, and has also made a study of the different factors which affect the measurements. Through field and greenhouse experiments he has been able to show how the diffusion currents measured with the platinum microelectrode can be related not only to the oxygen content

of the soil, but also to soil structure and plant growth. Similar findings have also been reported by Wiersma and Mortland 1953, Archibald 1952, Cline 1957, Jackson 1956, Scott 1959, and Brandt 1960.

The advantages of the microelectrode technique for characterizing soil aeration are:

1) The measurements of the oxygen diffusion rate (ODR) can be made under natural field conditions with very little disturbance of the soil. Measurements can also be made to practically any depth.

2) The method measures directly the availability of oxygen in the soil, in much the same way as the plant roots experience it, and is therefore an excellent method with which to characterize soil aeration.

3) The principle on which the method is based is simple and there are few if any complications involved in the use of it. The apparatus is also both simple and inexpensive to make.

4) Because of the micro-nature of the electrode and the heterogeneity of the soil, arrangements have been made so that 40 separate ODR measurements can be made in 25 minutes. From these values an average ODR value is calculated, with which to characterize the aeration conditions of the soil as a whole. Although individual readings will be found to vary noticeably, the average value of 40 such readings will generally be found to be very consistent. Few soil testing methods give better reproducibility or are capable of more accurately characterizing a particular soil property than this method.

5) The method does not require the collection of soil samples or any tedious mathematical treatment of the data collected. Twenty-five minutes is the total time required to receive a measure of the average

oxygen diffusion rate in a soil sample. The main disadvantages with the method are that:

1) It is very temperature sensitive and the ODR will change by 2.8 per cent degree change in temperature, see Van Doren 1958.

2) The electrodes become poisoned after long usage or if left exposed to the soil for any length of time, so that the ODR values measured become too high. Thus, it is not possible to leave the electrodes in the soil for the purpose of making continuous readings over a longer period of time. The electrodes must also be regularly cleaned in order to maintain their stability in readings.

3) The exact area of the electrode surface which is functioning when measurements are made is difficult to check. In most cases the whole area is actively contributing to the ODR, but at moisture tensions exceeding one atmosphere, there is always a risk that part of the surface will not be adequately covered with a moisture film. In such cases the ODR readings found will be too low. The electrode will therefore be limited in use to the higher moisture ranges of the soil. Since aeration, however, is seldom a problem in the dry range, where the electrode fails to function, this is hardly a serious disadvantage of the instrument.

The relation between plant growth and oxygen diffusion rate (ODR) of the soil as measured with the platinum microelectrode has been studied by Erickson and Van Doren 1960. They found in greenhouse studies that the emergence of sugar beets and potatoes was reduced by ODR values less than about 40×10^{-8} gm cm^{-2} min^{-1}. The growth of peas, tomatoes, sugar beets and corn was also reduced by ODR values below certain "minimum" rates. The value of the minimum ODR was found to vary according to the type of plant studied and also to the general nature of the environment, such as the light, temperature and fertility conditions, etc. Nevertheless, for given conditions it seems possible to determine the minimum rates below which different plants will suffer from oxygen deficiencies.

Under field conditions, Erickson and Van Doren found that the ODR varied in a cyclic fashion depending on the alternate wetting and drying of the soil caused by the action of weather, drainage and other factors. Only during relatively short periods did the ODR fall below the minimum range, which under greenhouse conditions had been found to be detrimental to the plants. Even short periods were, however, found to injure the plants especially when they occurred during very active periods of the plant's life, such as at germination and bloom. Thus the yield of peas was reduced by one third when they were subject to a 24-hour long oxygen deficient period just before bloom. Tomato plants were also stunted in their growth by early oxygen deficient periods. It therefore seems that an important measure of the aeration properties of the soil would be to measure the length of time over which it is oxygen deficient for a particular plant. For the purpose of comparing the aeration properties of different soils a measure of the rate of recovery of the ODR after a uniform water application would also seem to be of great significance to plants.

Wiegand and Lemon 1958 have made an attempt to bridge the gap between the knowledge of the oxygen requirements of roots, which has been gained through laboratory studies by plant physiologists and that gained through field studies by agronomists. From the literature they have found values determined for the consumptive use of oxygen for wheat and onion roots and also critical oxygen concentration values, below which the supply of oxygen to these roots is inadequate and causes injury. By using the platinum microelectrode to measure the oxygen diffusion rate of a given soil and by assuming values for the oxygen concentration gradient and diffusion coefficient which are active in the soil, they are able to solve the rate equation for the corresponding film thickness L.

Knowing the L value of the soil, they then rearrange the rate equation again and use the rate of consumptive use and critical oxygen concentration taken from the literature to determine the concentration of oxygen C_r, which will occur at the root surface for the soil conditions studied. If the calculated C_r value is equal to or greater than the critical oxygen concentration obtained from the literature, they assume that soil aeration is adequate, whereas if C_r is less than this value they believe that the soil will not be capable of meeting the plant root needs for oxygen.

Wiegand's and Lemon's work is a noteworthy contribution to our knowledge of soil aeration and its significance to plant roots. Their use of the plant root surface as a reference point for characterizing soil aeration is also very interesting, but the question arises how accurately the C_r values can be determined and what advantages this approach has in comparison with that using the oxygen diffusion currents directly as a measure of soil aeration conditions, Erickson and Van Doren 1960. The manipulations they use to convert the oxygen diffusion current to a C_r value, involves the use of many factors, the accuracy of which are rather questionable. Since laboratory data on consumptive use of oxygen by roots and their critical oxygen concentrations are rather scanty, it would seem better if the plant physiolcgist used the same tool as the agronomist to characterize soil aeration than vice versa. If direct measurements with the platinum microelectrode could be adequately correlated with plant growth as has already been demonstrated by Erickson and Van Doren 1960, this would seem to be the simplest way to characterize soil aeration.

C. Conclusions

From the preceding review of soil aeration and its relation to drainage, the following points can be brought out as being of special interest to the present investigation.

1) For maximum plant growth there must be an adequate supply of both water and oxygen from the soil to the plant roots.

2) Drainage is one of the main factors affecting the ability of the soil to supply water and oxygen to plant roots. As water drains from the soil, its ability to supply oxygen will increase at the same time as its ability to supply water will tend to decrease. Drainage must therefore be carefully regulated so that the supply of both these nutrients is maintained at the optimum rates required by plants. At present there is little if any information regarding these aspects of drainage.

3) Soil aeration is the process by which oxygen is supplied to the

roots. It consists of two closely integrated phases, one involving diffusion of oxygen through the gas-filled pores of the soil and the other diffusion of oxygen through the water films surrounding the plant roots.

4) The rate of diffusion of oxygen through the gas-filled pores of the soil is dependent on the volume and structure (tortuosity) of these pores. This process governs the rate of supply of oxygen from the atmosphere to the root zone and greater depths in the soil.

5) The rate of diffusion of oxygen through the water films surrounding the roots will depend on the film thickness. In the upper parts of the soil (the surface soil) where the atmospheric air is close at hand, this process will be more important in determining the rate of supply of oxygen to the plant roots than the oxygen diffusion through the gas-filled pores.

6) The ability of the soil to supply oxygen to the roots will depend on three main factors:

a) The Capacity Factor Q which represents the total amount of oxygen contained in the soil at any given time.

b) The Intensity Factor C, which is a measure of the concentration or partial pressure of oxygen at any given point in the soil.

c) The Rate Factor F, which represents the amount of oxygen that can be supplied by the soil to any given point per unit of time. All three of these factors will be affected directly or indirectly by drainage.

7) Soil aeration is best characterized by means of the Rate Factor,

since this takes into account both of the other two factors and also the nature of the soil environment. In mathematical terms the Rate Factor for the aeration process through the moisture film surrounding a plant root can be expressed by the equation

$$F = D\,A\,\frac{(C_p - C_r)}{L}$$

where D is the diffusion coefficient of oxygen through the moisture film, A is the surface area of the root, $(C_p - C_r)$ is the difference in oxygen intensity of the moisture film at the root surface and at the air-water interface, and L is the thickness of the moisture film. The length of time over which the intensity gradient can be maintained across the film will depend on the capacity of the soil for oxygen.

8) The platinum microelectrode technique has proved to be an excellent method with which to measure the oxygen diffusion rate (Rate Factor) through the liquid phase of the soil. Measurements with the electrode correlate very well with plant growth response under conditions where soil aeration is not adequate for the proper functioning of the roots.

CHAPTER III

FIELD STUDIES

A. Introduction

1. Purpose

The purpose of the field studies was to investigate under various field conditions the effects of drainage on the aeration properties of surface soils. The platinum microelectrode, which acts as an oxygen absorber or plant root simulator and measures the rate of oxygen diffusion through the liquid phase of the soil, was used to characterize the soil aeration conditions.

2. Sites

The field studies were made at five locations, where the natural drainage conditions were poor and had to be improved artificially to make possible intensive crop production. These were:

1. The Soil Science Farm, East Lansing, Michigan
2. The Farm Crops Farm, East Lansing, Michigan

3. The Ferden Farm, Chesaning, Michigan

4. The Crawford Farm, Dafter, Michigan

5. The North-Central Substation of the Ohio Agricultural Experiment Station, Castalia, Ohio

At the first three locations, the land had been tile-drained according to conventional methods, while at the last two different types of tile and surface drainage had been installed for experimental purposes.

3. Methods

By limiting the studies to the surface layer of the soil, only the diffusion of oxygen through the liquid phase of the soil had to be considered in characterizing the aeration process to the plant roots. The closeness of the atmosphere would ensure a high rate of oxygen diffusion through the gaseous phase and keep this at an oxygen concentration essentially the same as in the atmosphere for depths less than 6 inches. Thus the oxygen diffusion rate through the liquid phase as measured with platinum microelectrode should fairly well characterize the aeration conditions of the soil that are of significance to the plant roots.

A photograph of the platinum microelectrode apparatus used in this investigation for characterizing the aeration properties of the soil, is shown in Figure 2. The electrodes each consist of a short piece of 22 gauge (0.064 cm diameter) platinum wire which is fused to a 12 gauge plastic insulated wire that acts as a support and electric lead. The union between the platinum and copper wire is covered by special adhesive material, so that no part of the copper wire

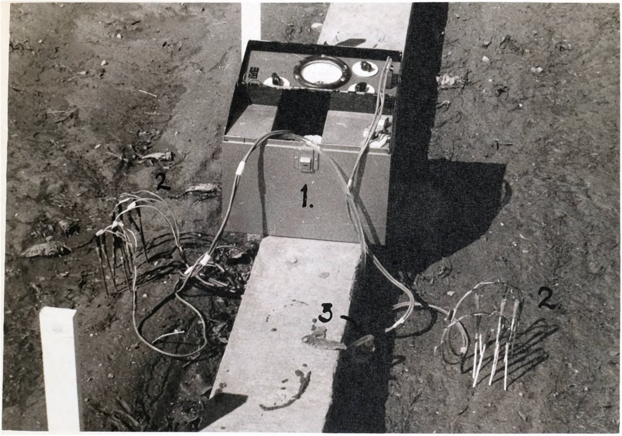


Figure 2. The platinum microelectrode apparatus set up for measurements in the field.

1. Instrument box containing electric circuit.

2. Set of 10 electrodes connected to the instrument box.

3. Porous cup with plastic tube, which is the KCl bridge to the standard cell.

is exposed at this end of the electrode. The length of the platinum wire is trimmed to 4 mm, giving it an active area of 0.08 square centimeters.

The total length of the electrode is 6 inches so that measurements of the oxygen diffusion rate of the soil can be conveniently made to depths of 4 inches.

When measurements are to be made, the microelectrode is inserted in the soil to a depth of 4 inches and a potential of 0.65 volts is applied between the microelectrode (cathode) and a silver-silver chloride reference electrode (anode) contained in a portable instrument box. This box also holds a 2-volt wet cell battery to supply the necessary voltage and a 20 microampere DC microammeter to measure the current.

The contact between the platinum electrode placed in the soil and the silver-silver chloride reference electrode contained in the box is made by means of a salt bridge. This consists of a length of plastic tubing, which is filled with saturated KCl solution and leads from the reference cell to a porous ceramic cup placed in the soil. Due to the potential applied, oxygen occurring in the soil solution at the surface of the platinum microelectrode is reduced to water, causing an electric current to flow which can be measured on the microammeter. This current is proportional to the rate at which oxygen is diffusing from the soil medium surrounding the electrode to its surface. Because of the micro-nature of the electrode and the heterogeneity of the soil, it has been found necessary to determine the average current value from 40 separate electrode readings, in order that a truly representative value of the oxygen diffusion rate of the soil medium may be obtained. To facilitate this number of measurements, the field apparatus shown in Figure 2 has been constructed to allow 10 microelectrodes to be used simultaneously. The time required for a complete determination to be made (i.e., 40 electrode readings) is about half an hour. In the present investigation, however, arrangements were made so that two instrument boxes could be used simultaneously and 80 readings, giving two average values, could be obtained in half an hour.

Since the oxygen diffusion currents produced at the microelectrode are temperature dependent, some measure of the temperature of the soil is also necessary so that the readings obtained at different locations and different times can more accurately be compared. In this investigation the soil temperature was determined to the nearest degree Fahrenheit with bimetallic type thermometers, which were pushed into the soil to the same depth as the electrode (i.e., 4 inches).

The oxygen diffusion current, measured in microamperes with the platinum microelectrode apparatus, will be abbreviated in the following report by the letters ODC. This value can also be converted into an oxygen diffusion rate value, abbreviated ODR, by expressing it as the number of grams of oxygen that diffuse per minute to each square centimeter of the electrode surface. This is easily done, since it is known that (see Lemon and Erickson 1952):

$$i = 10^6 nFAf \tag{16}$$

where i = the ODC measured in microamperes.

$n = 4$, the number of electrons used for the reduction of each molecule of oxygen.

F = 96,500 coulombs, the Faraday

A = 0.08 square centimeters, the area of the surface of the electrode.

f = the flux of oxygen to the electrode surface expressed as moles of oxygen diffusing to each square centimeter of electrode surface per second.

From equation (16):

$$f = \frac{i}{10^6 nFA} \quad \text{moles } O_2 \text{ cm}^{-2} \text{ sec}^{-1}$$

Since the oxygen diffusion rate is to be expressed in grams per minute instead of moles per second:

$$ODR = f \times 32 \times 60 \quad \text{gm } O_2 \text{ cm}^{-2} \text{ min}^{-1}$$

$$ODR = \frac{32 \times 60 \times i}{10^6 nFA}$$

$$ODR = 6.2 \times 10^{-8} \times i \quad \text{gm } O_2 \text{ cm}^{-2} \text{ min}^{-1} \tag{17}$$

When soil aeration conditions are to be characterized, the average ODC value of 40 microelectrodes inserted in the surface soil is determined and then converted into the equivalent ODR value by using equation (17) above.

The effects of drainage on the aeration conditions of the surface soil were studied from two different aspects in this investigation. These were:

a) The effects of different methods and intensities of drainage on soil aeration. To study this aspect, ODR measurements were made at different distances perpendicular to the drainage facility (i.e., to the tile line in the case of tile drainage or to the bed ridge in the case of bedding) to see what effects these distances would have on the ODR values obtained. Areas at distance of 0-2, 5-10 and 15-20 feet on either side of the tile or bed ridge were chosen for these measurements. In this way it was possible to compare the relative effects of both different types and different intensities of drainage treatment on the ODR values (aeration conditions) of the soil.

b) The effects of different drainage conditions on the rate of increase of soil aeration with time. This was studied by determining the ODR at regular time intervals in the same positions in the field and expressing these values as a function of time. The time-rate of change of ODR could then be used to characterize the efficiency of different types and intensities of drainage, since this value is a measure of how quickly the soil will recover from poor aeration conditions caused by excess moisture.

Besides making aeration measurements of the surface soil, the moisture conditions were also characterized using different methods. Thus, at the same time as the ODR measurements were made, soil samples were also taken to a depth of 4 inches and gravimetric determinations made of the moisture content. The depth of the water table was determined whenever possible by means of 3/4 inch diameter perforated tubes installed to a depth of 4 feet. At locations 1 and 3 tensiometers were installed at various depths, where the ODR measurements were made, in order to determine the moisture tension at these sites during the course of drainage.

In order to better understand the relation that existed between the moisture content and the degree of drainage of the different soils, core samples 3 x 3 inches in dimension were taken of each soil in its natural state from 1 to 4 inches depth. These cores were saturated with water in the laboratory and then placed on moisture extraction tables to bring them in equilibrium with suctions varying from 10 to 60 cm of water. Suctions of 1/3 and 1 atmosphere were applied by use of a pressure plate extractor. The weights of the cores were recorded for each suction applied and also after oven drying at 105°C. From this data moisture retention curves were constructed to show how the moisture content changed for each soil from 0-1 atmosphere moisture suction.

Information regarding the inverse relationship which exists between the soil air and water factor could be obtained by comparing the moisture data collected with the corresponding soil aeration (ODR) data. The relationship between these factors forms the basis to a real understanding of the effects of drainage on the aeration conditions of a particular soil and is of fundamental importance for the correct design of drainage systems from an edaphic point of view.

B. The Soil Science Farm

1. Description of Site

In the spring of 1960, soil aeration studies were carried out at the sugar beet field, which is situated in the south part of the Soil Science Farm, Michigan State University. The soil comprising the field is classified as being partly Brookston loam (a poorly drained Humic Gley soil) and partly Conover loam (an imperfectly drained Gray-Brown Podzolic soil), both of which are rather common in southern Michigan. When artificially drained both soils are well adapted for use as cropland. The field was tile-drained in 1955 and 4 inch tile lines were installed with a spacing of 44 feet and a depth of 3 feet. A map of the field showing its location and topography and the design of the drainage system is given in Figure 3.

At the beginning of April 1960 the middle part of the field was completely covered by several inches of water, which was prevented from draining away from the area by a root block that occurred in the main outlet line. This situation was of some advantage for the following studies, however, since it allowed the soil to initially become more thoroughly saturated with water than would normally have been the case had the tiles been functioning.

2. Experimental Design and Methods

On April 9, three stations for aeration studies were established on the sugar beet field. Station I was selected to lie between tile lines 2 and 3 (see Figure 3) about 100 feet south of the main outlet line. At this time two inches of water still covered the soil surface in this area and boards to walk on were therefore laid out perpendicular to and between the two tile lines. Stakes were set up to indicate distances from the tile lines, which will be referred to here as the East and West tile lines respectively.

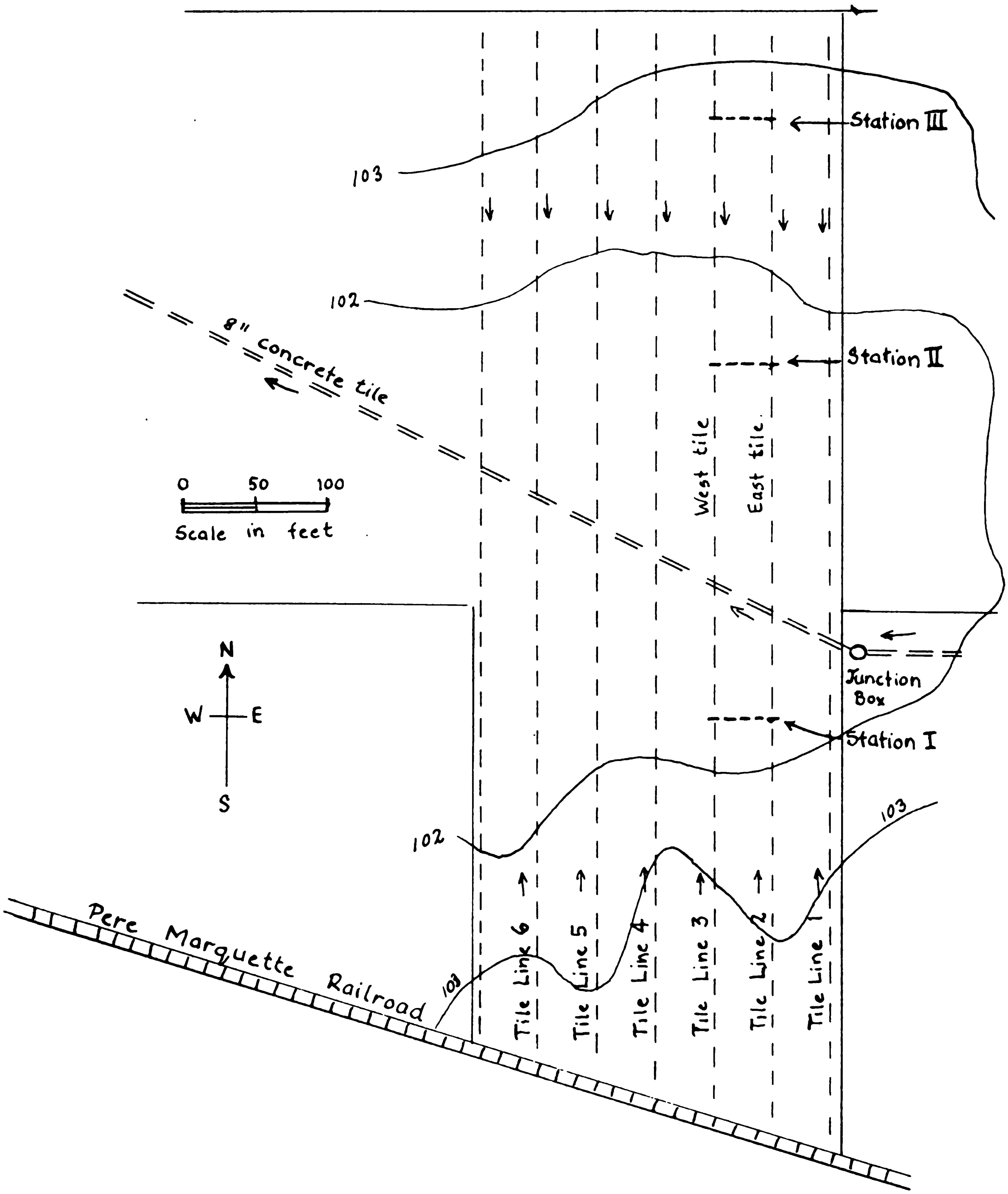


Figure 3. Map of the sugar beet field at the Soil Science Farm, Michigan State University, showing the tile lines and the locations of Stations I - III.

On April 12, only traces of surface water remained in the area and at this time tensiometers and ground water wells were installed and the first set of ODR determinations were made. The elevation of the soil surface where the aeration studies were made was determined relative to the bottom of the junction box on the east side of the field and is shown in Figure 4 together with some of the measurements made of the ground water elevation. Photographs of Station I were taken on April 9 and 12 and are shown in Figure 5. The moisture retention curve for the soil is given in Figure 6.

In order to supplement the measurements made at the main site (Station I), two other sites were selected at higher elevations in the field. Thus Station II was located between the same two tile lines but 300 feet north and about one foot in elevation higher up in the field than Station I, while Station III was chosen about 500 feet north of and two feet above Station I (see Figure 3). Tensiometers and ground water wells were not installed at these stations.

3. Results and Discussion

The results of the studies made at the three stations can appropriately be divided into two separate periods--the first period, from April 12 to 25, during which the main was blocked, and the second period, from April 26 to May 5, when the block had been removed and the drainage system was functioning normally.

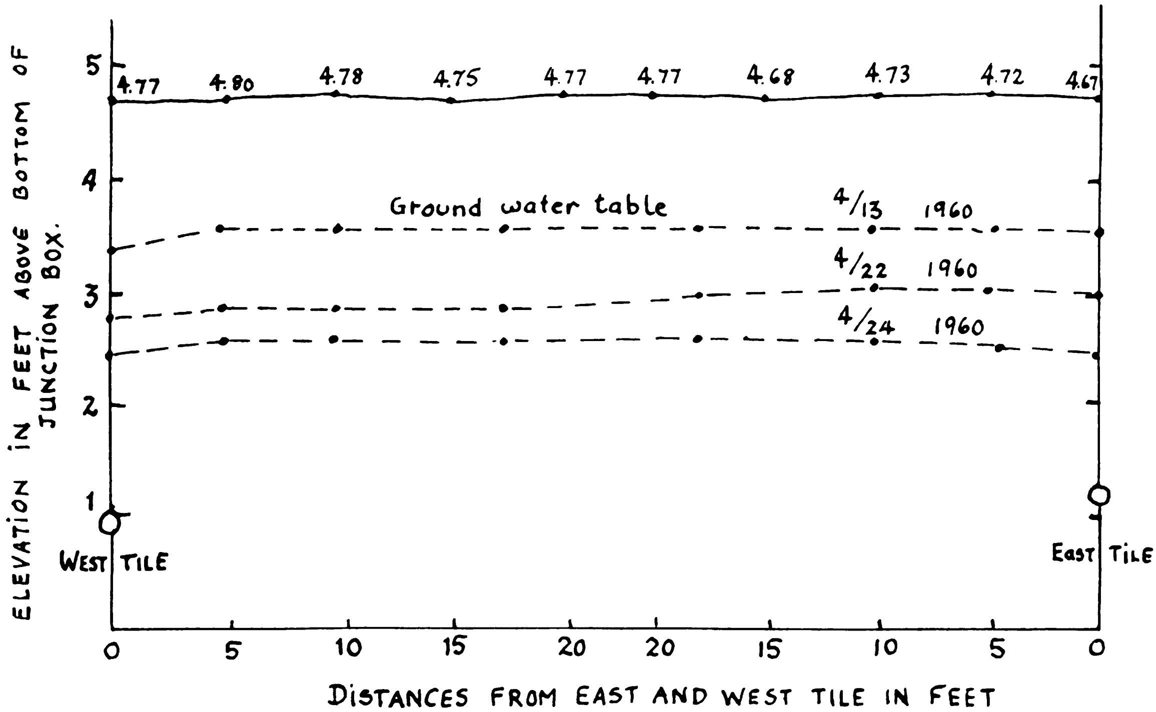


Figure 4. Level of land surface and depth of tile lines at Station I, Soil Science Farm. The height of the ground water table measured on three different dates is also shown (the tile system was blocked during this period).

April 9, 1960

April 12, 1960

Figure 5. Station I at Soil Science Farm. The tile lines run perpendicular to the boards and the stakes mark regular distances from them.

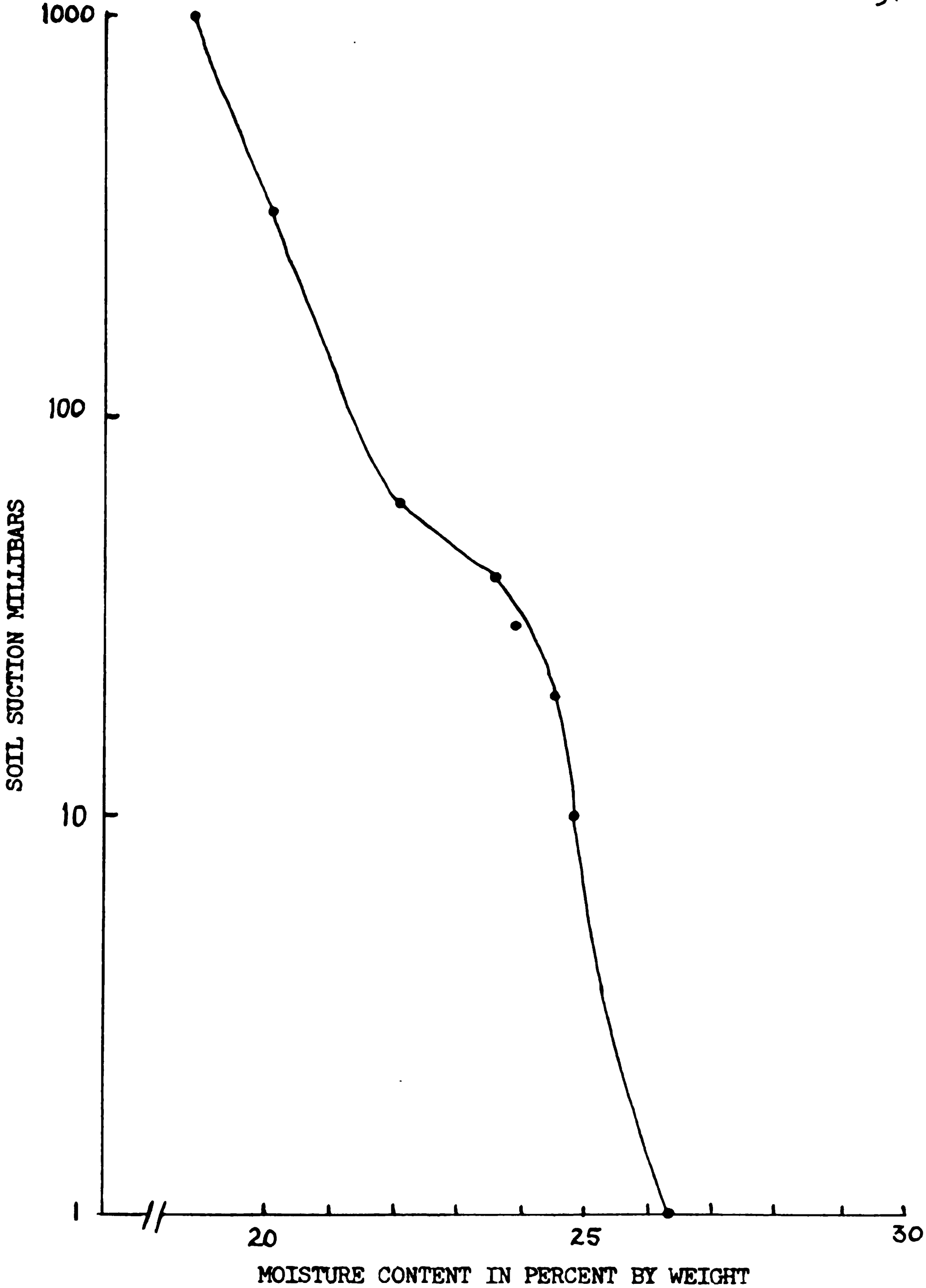


Figure 6. Moisture retention curve for Brookston loam from Station I, Soil Science Farm.

Station I (The first period--April 12-25). Six series of ODR and soil moisture determinations were made between the tile lines during the first period and the results are presented in Table A of the Appendix. The measurements made of the ground water table depth are presented graphically in Figure 4 and the tensiometer readings made at various depths and distances to the tile lines are shown in Table 1.

The fact that the tile drainage system was not functioning during this period was reflected in all the measurements made. Thus the ground water table was practically horizontal the whole distance between the tile lines and showed little if any indication of a draw-down effect above the tile lines (see Figure 4). During the whole period the water level dropped from a depth of about one foot to a depth of just over two feet from the soil surface. Most of the tensiometers registered zero tension throughout this period, see Table 1. Small tension values were observed at 6 inches depth, especially towards the end of the period (April 24).

The ODR and soil moisture content values measured at various distances from the tile and on different dates are plotted in Figure 7 (see also Table A in the Appendix). From this it is evident that the distance to the tile lines had no real effects on the ODR and moisture content values of the surface soil (4 inch depth). With the exception of the ODR curves for April 21 and 22, which are rather irregular, the other ODR curves shown in the upper part of Figure 7 as well as the moisture curves shown in the lower part are very flat. In most cases the values measured midway between the tiles (i.e., at 15-20 feet) are identical with the average values calculated for the whole area

TABLE 1

TENSIOMETER READINGS MADE ACROSS THE TILE LINES AT STATION I, SOIL SCIENCE FARM. VALUES EXPRESSED IN PERCENT OF AN ATMOSPHERE MOISTURE SUCTION

Date 1960	Depth in inches	Distance From Tile in Feet East 0	3½	7½	17½	7½	West 3½	0
April 12 (one hour after installation)	6	0	0	0	0	0	0	-
	12	0	0	0	0	0	0	0
	24	0	0	0	0	-	-	-
April 13	6	2	3	0	0	0	0	0
	12	0	0	0	0	4	0	0
	24	0	0	0	0	-	-	-
April 13	6	5	7	0	0	3	1	0
	12	0	0	0	0	7	3	3
	24	4	4	0	0	-	-	-
April 22	6	8	14	2	5	air leak	6	0
	12	0	0	0	0	8	3	3
	24	4	5	0	0	-	-	-
April 24	6	19	28	10	13	air leak	13	10
	12	0	0	5	0	11	4	5
	24	7	6	0	1	-	-	-
April 26 (six hours after heavy rain)	6	0	0	0	0	0	0	0
	12	0	0	0	0	0	0	0
	24	0	0	0	0	-	-	-
April 29	6	4	6	4	2	34(?)	6	3
	12	0	0	0	0	1	0	0
	24	2	1	0	0	-	-	-
May 2	6	0	0	0	0	(?)	0	0
	12	0	0	0	0	0	0	0
	24	2	1	0	0	-	-	-

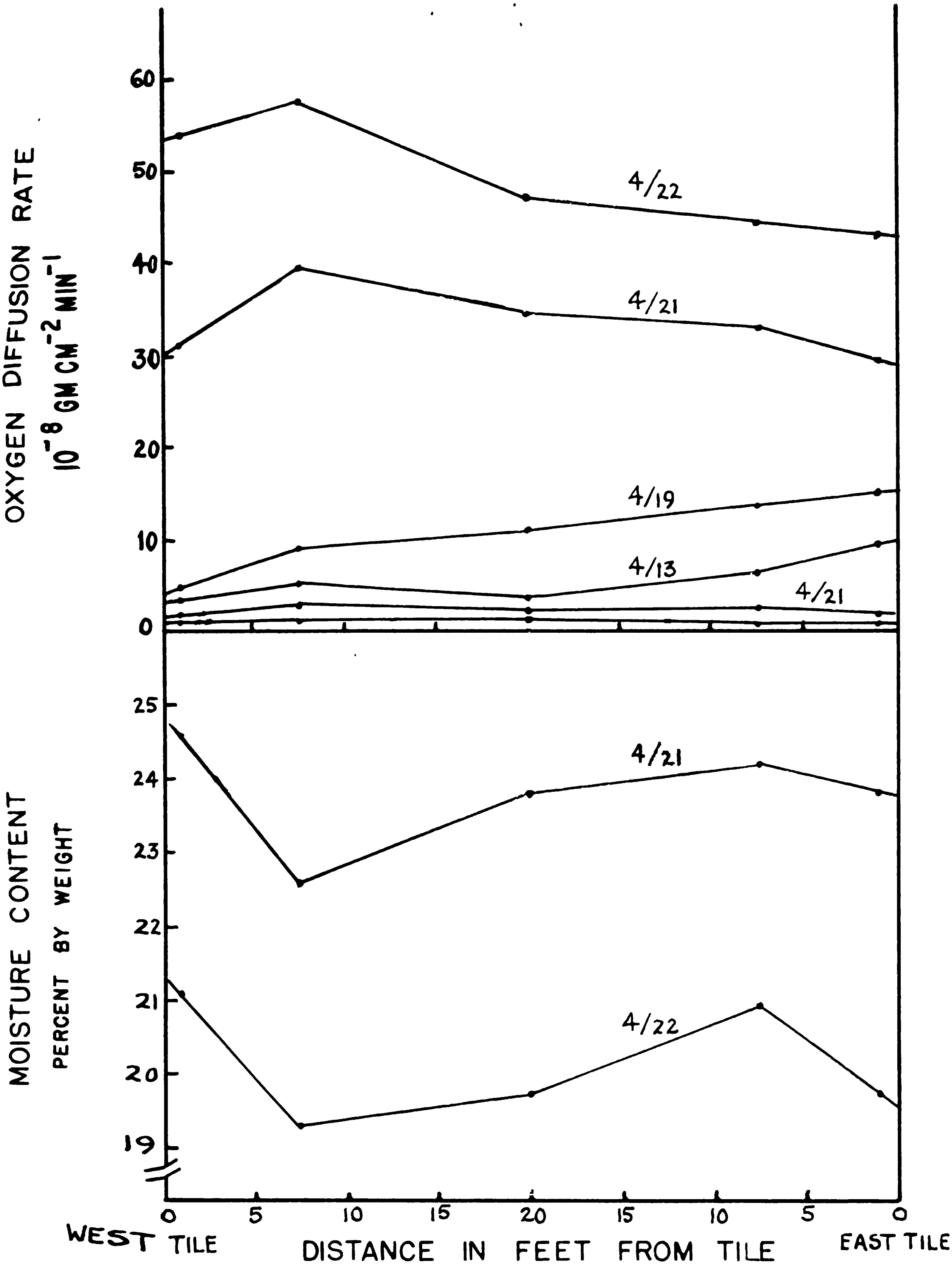


Figure 7. The ODR and soil moisture content measured between the two tile lines during the first period (April 12-25) when the tile system was blocked at Soil Science Farm.

between the tiles, which further indicates that the tiles had very little if any effect in decreasing the soil moisture content or improving the oxygen diffusion conditions of the surface soil. The water loss that did occur during the ten-day period must therefore have been removed by deep seepage and evaporation. Very little was seen to escape through the blocked tile system.

Station I (The second period--April 26-29). The main drain was cleared in the morning of April 25. In the afternoon of the same day and early morning of April 26 more than one inch of rain fell. Despite this and the fact that a water table had been measured at a depth of 2 feet only 48 hours earlier, it was not possible to detect any water table to a depth of 3 feet in the afternoon of April 26. This would indicate that the soil is extremely permeable and the drainage system very effective in removing free water from the field.

ODR and moisture determinations were made on April 26 and April 29, see Table A in the Appendix. Figure 8 shows how these values vary with the distance to the nearest tile line. The curves for April 26 are fairly flat, but do show a slight effect of the tile lines. For April 29 the ODR and soil moisture content curves show a very distinct and consistent effect of both tile lines. From Table A it is seen that the ODR value at the 15-20 feet location is on an average 42×10^{-8} gm O_2 cm^{-2} min^{-1}, whereas at the 0-2 feet location it is on an average 51×10^{-8} gm cm^{-2} min^{-1}, which is an increase of about 20%. The difference in the soil moisture content is relatively much less. The content at the 0-2 feet location is only 0.6% lower than that at the 15-20 feet location (16.6% as compared with 17.6%).

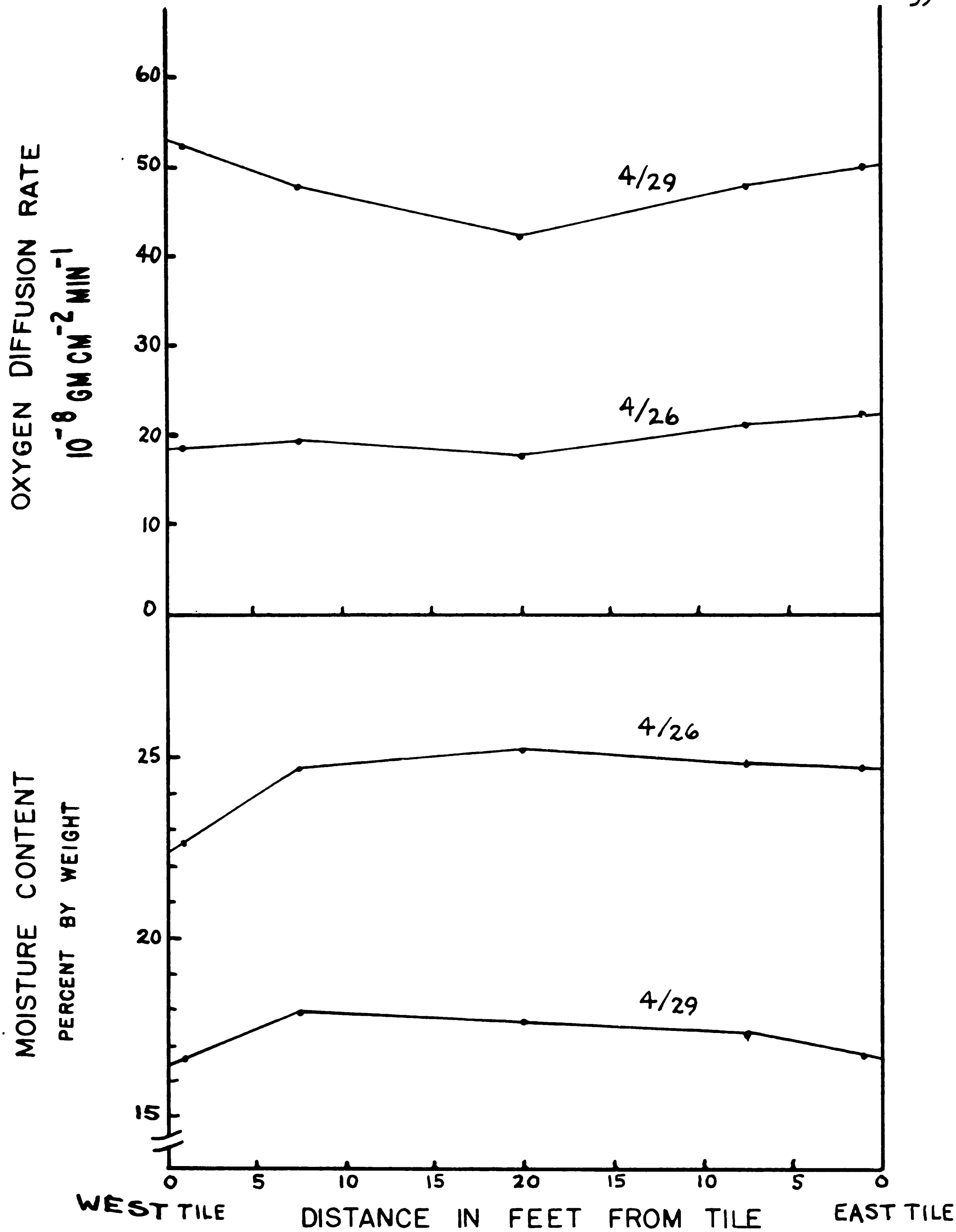


Figure 8. The ODR and soil moisture content measured between the two tiles during the second period (April 26-29) when tile system was functioning at the Soil Science Farm.

Station I (The complete period--April 12-29). In Figure 9 the average ODR and also the corresponding average soil moisture content values have been plotted for the whole period from April 12 to 29. The precipitation received during the same period has also been drawn in with short columns at the bottom of the diagram to show the date and amount of each rainfall. Since measurements were only taken on seven of the total eighteen days, the curves joining the points have been schematically extrapolated to show the manner in which they varied during the entire period. It will be noticed that immediately after each rain, the ODR value of the soil decreased rapidly to a very low value, while in quite the opposite manner the moisture content values rapidly increased. After the rain had stopped both values started to return slowly again to their original values. Thus the ODR values steadily increased as the soil moisture values decreased, until when the next rain came the values again changed in a reverse fashion. The inverse relationship between the ODR and moisture content of the soil is very nicely illustrated in Figure 9, where the two curves are seen to form almost perfect mirror images of one another.

Stations II and III. Stations II and III, which were established to supplement Station I, may conveniently be discussed together. The values of the ODR and soil moisture contents are found in Table B of the Appendix. The manner in which the ODR and moisture content values vary with distance to the tile are graphically illustrated in Figure 10. The ODR values are seen to increase while the moisture contents decrease as the tile lines are approached, especially for the values

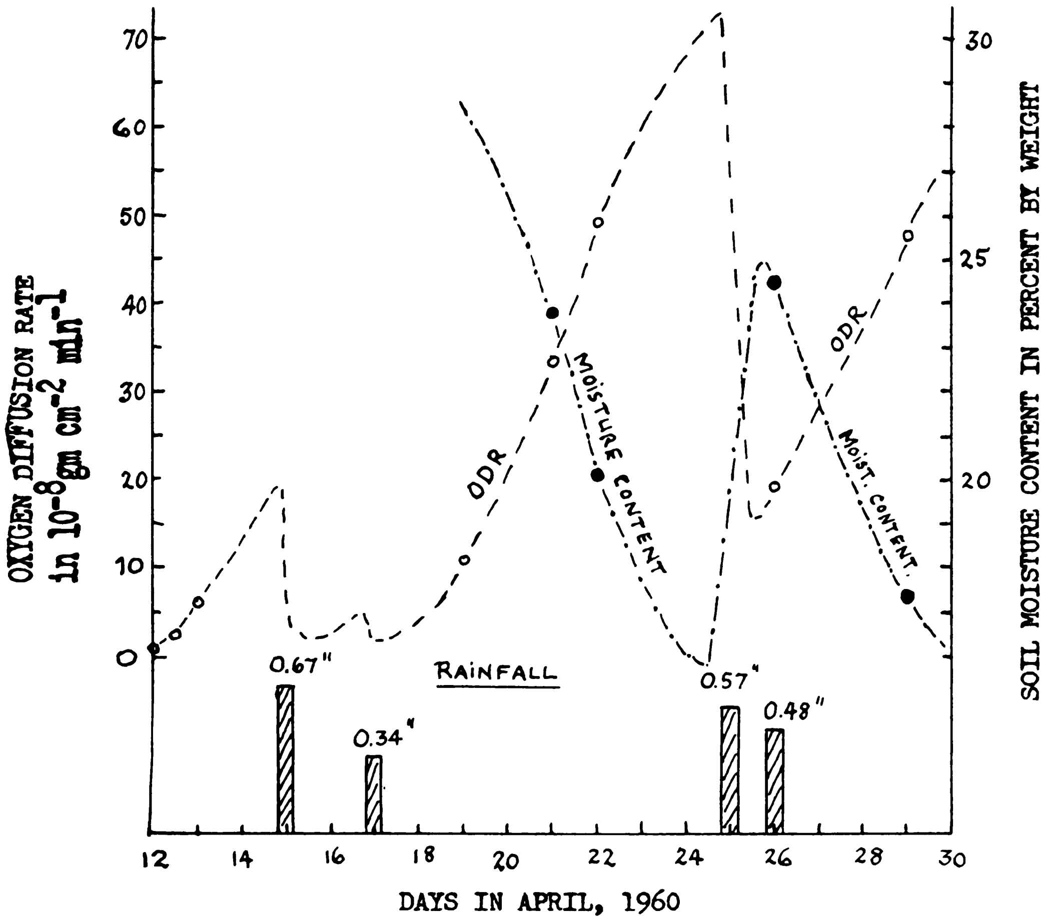


Figure 9. The change in the average ODR and moisture content values in the surface soil (4 inch depth) at Station I, Soil Science Farm, during April, 1960.

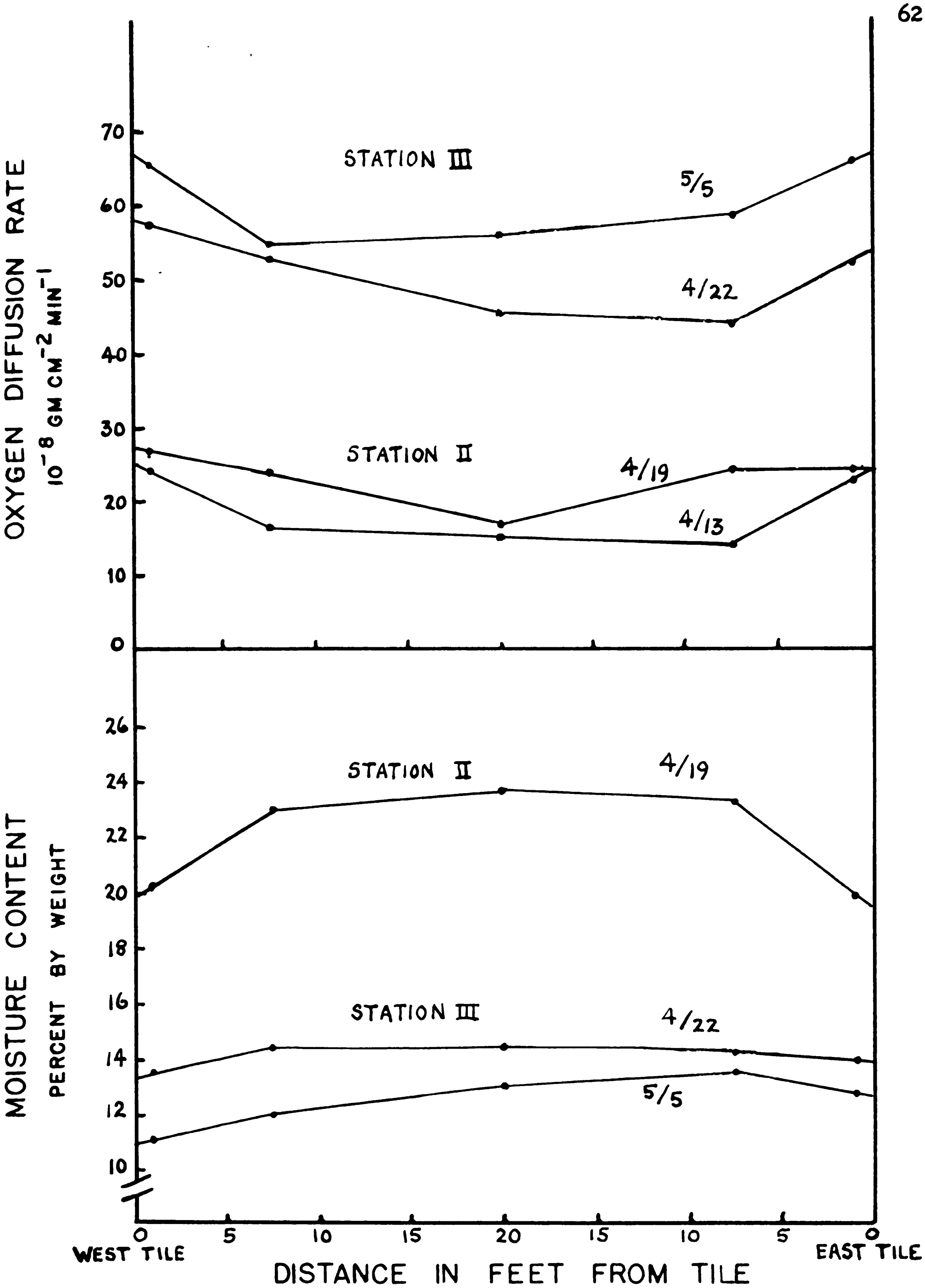


Figure 10. The ODR and soil moisture content measured between the two tile lines at Stations II and III, Soil Science Farm.

obtained at Station III. Unfortunately the measurements made at these two stations were not made on the same dates and can therefore not be compared directly. It should be observed that the main reason why the ODR curves for Station III are always higher than those for Station II is because the measurements for Station III were made later than at Station II, when the moisture contents were lower.

Stations II and III can be compared with Station I for certain dates. Thus the ODR values taken on April 19 at Stations I and II and the ODR and moisture content values taken on April 22 at Stations I and III can be compared (compare Figures 7 and 10). From these it will be seen that in both cases Station I gave lower ODR values and higher moisture content values than Station II or III. Since the soil conditions are very similar at all three stations, these differences reflect the influence of elevation on drainage effects. Thus on April 19 a one foot increase in elevation changes the average ODR of the soil from 10.7 (Station I) to 23.3 x 10^{-8}gm O_2 cm^{-2} min^{-1} (Station II).

<u>The Relationship Between ODR and Moisture Content of the Soil</u>. Throughout the previous discussion of the data collected at the three stations, the inverse relationship between the ODR and moisture content values has been clearly demonstrated. Thus whenever an increase or decrease in the soil moisture content was observed a corresponding decrease or increase, respectively, in ODR was also found. In order to more closely study this relationship, Figure 11 was constructed, where the average ODR and corresponding average moisture content values for all

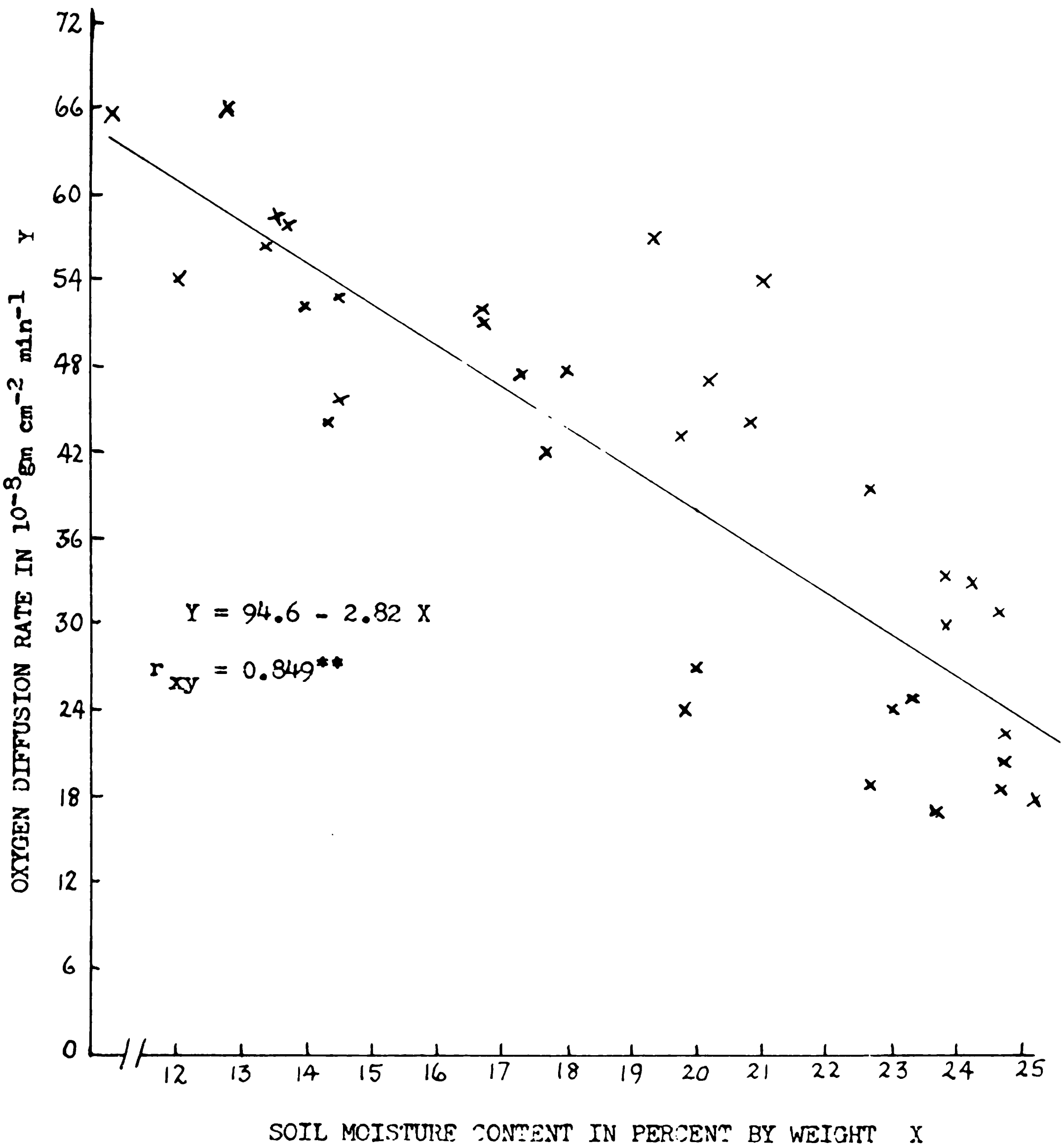


Figure 11. **Plot of ODR versus Soil Moisture Content for data from Soil Science Farm.** (Brookston loam)

three stations and all dates (see second last column in Tables A and B of the Appendix) were plotted. A simple linear correlation analysis was also made of this data to see if a suitable straight line relationship could be found. The analysis gave a regression equation, $Y = 94.6 - 2.82\,X$, which was significant at the 1 percent level (Y represents the dependent ODR variable measured in 10^{-8}gm O_2 cm^{-2} min^{-1} and X the independent soil moisture content variable measured in percent by weight of the oven-dry soil). The regression line has been marked in on Figure 11.

4. Summary

When the tile-drainage system was out of order during the period April 12-25, the ODR and moisture content values measured across the field at Station I were uniform and independent of the distance to the nearest tile line.

When the tile-drainage system was functioning normally after April 25, both the moisture content and the ODR values of the surface soil were affected by the distance to the nearest tile line. Thus the moisture content decreased as one of the tile lines was approached at the same time as the corresponding ODR increased.

When moisture contents and ODR values were measured on the same dates and compared between the three stations, differences were observed which could be accounted for by the difference in elevation between the stations. This indicates that the elevation of the soil is also an important drainage factor to take into consideration.

When the changes in ODR and moisture content of the surface soil were studied with time, a cyclic reciprocal relationship was observed between these two properties, due to the effects of weather. Thus, rain increased the moisture content of the surface soil at the same time as it decreased the ODR. When dry weather followed, the moisture content gradually decreased at the same time as the ODR gradually increased. The rate of increase of ODR with time after a rain is an important measure of the drainage properties of the soil and field, since it determines the period over which plant roots living in the soil will experience oxygen deficiencies.

When the moisture content and corresponding ODR were related to one another a highly significant linear relationship was obtained. The regression equation found was $Y = 94.6 - 2.82\,X$, where Y represents the ODR value and X the moisture content.

C. The Farm Crops Farm

1. Description of Site

On the South Field of the Farm Crops Farm at Michigan State University a tile system was installed in June 1959. During the spring of 1960 a study of the soil aeration and drainage conditions of the surface soil was made across one of the tile laterals on this field, the location of which is more precisely shown in Figure 12.

The soil in the South Field is classified as Conover loam, an imperfectly drained Gray-Brown Podzolic soil, which requires artificial drainage to make it suitable for intensive crop production.

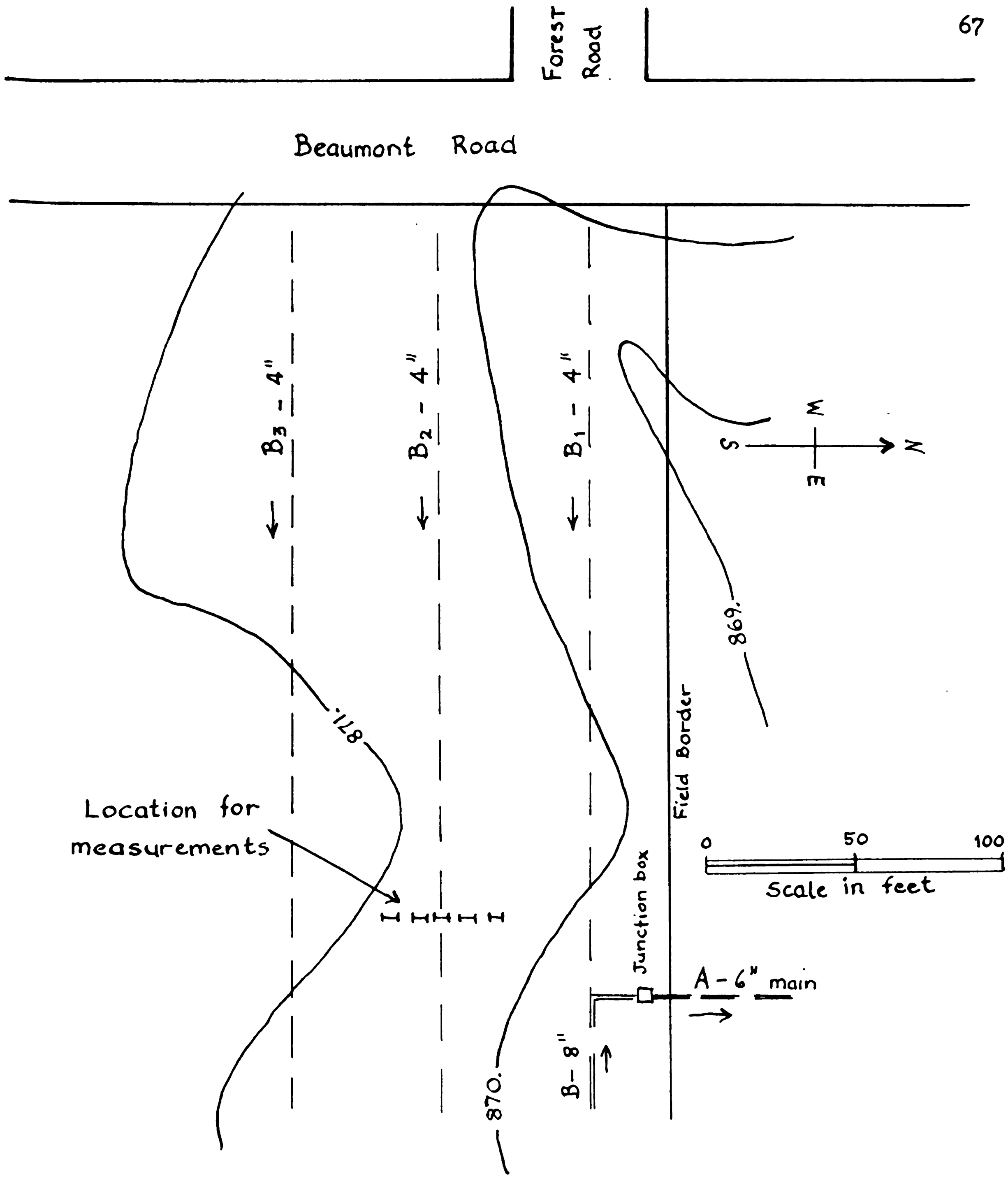


Figure 12. Map of South Field at Farm Crops Farm showing tile lines and location where measurements were made.

Figure 13. View over the South Field at the Farm Crops Farm looking northwest. Notice how the tile lines affect the field drainage pattern.

Prior to 1959, when 4 inch lateral tile lines were installed at an average depth of 3 feet and a spacing of 50 feet, the field had for many years been used as grassland. In the fall of 1959 it was plowed and disc-harrowed several times in preparation for cropping in 1960. In the spring of 1960 the drainage effect of the new tile system was very noticeable in the field, where it was seen from the lighter color that the soil above the tile lines was much better drained than the soil occurring between them, see Figure 13.

2. Results and Discussion

Four series of ODR and corresponding moisture content values were measured across the tile line at this location between April 22 and May 5, 1960, see Table C in the Appendix. The moisture retention curve determined in the laboratory from soil core samples taken from the area where the aeration studies were made is given in Figure 14.

The average ODR and moisture content values obtained for each date when measurements were made, have been plotted as a function of time in Figure 15. The rain received between April 22 and May 5 is also shown in this figure. The ODR and moisture content values will be seen to be mainly affected by the rain received. If measurements had been made at closer intervals over the period, the effect of the rain on these properties would probably have been better illustrated. Both the ODR and moisture content curves in Figure 15 would most certainly have shown sharper breaks than now shown immediately following the rain showers, and a more gradual recovery would also have been noticeable

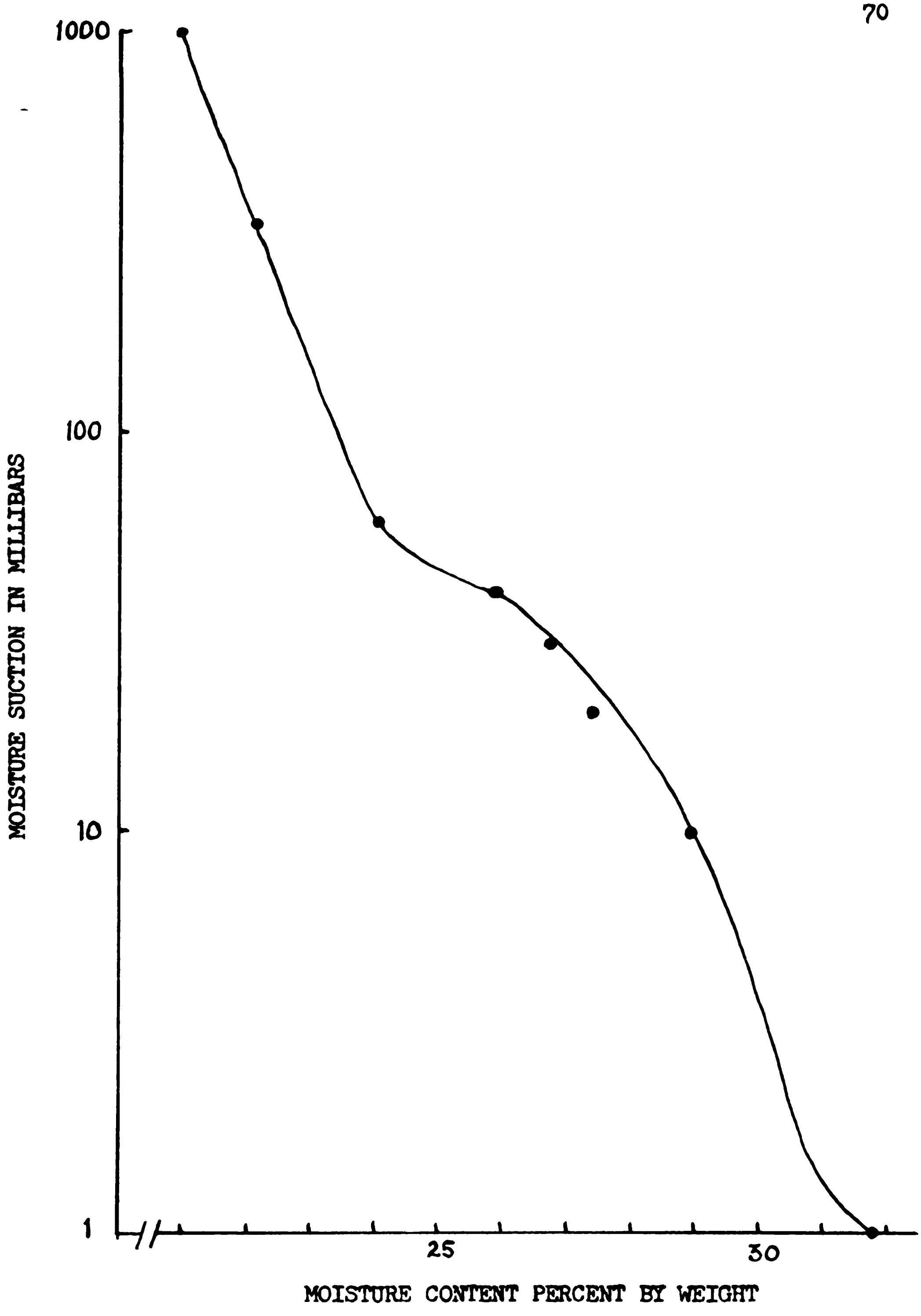


Figure 14. Moisture retention curve for Conover loam from Farm Crops Farm.

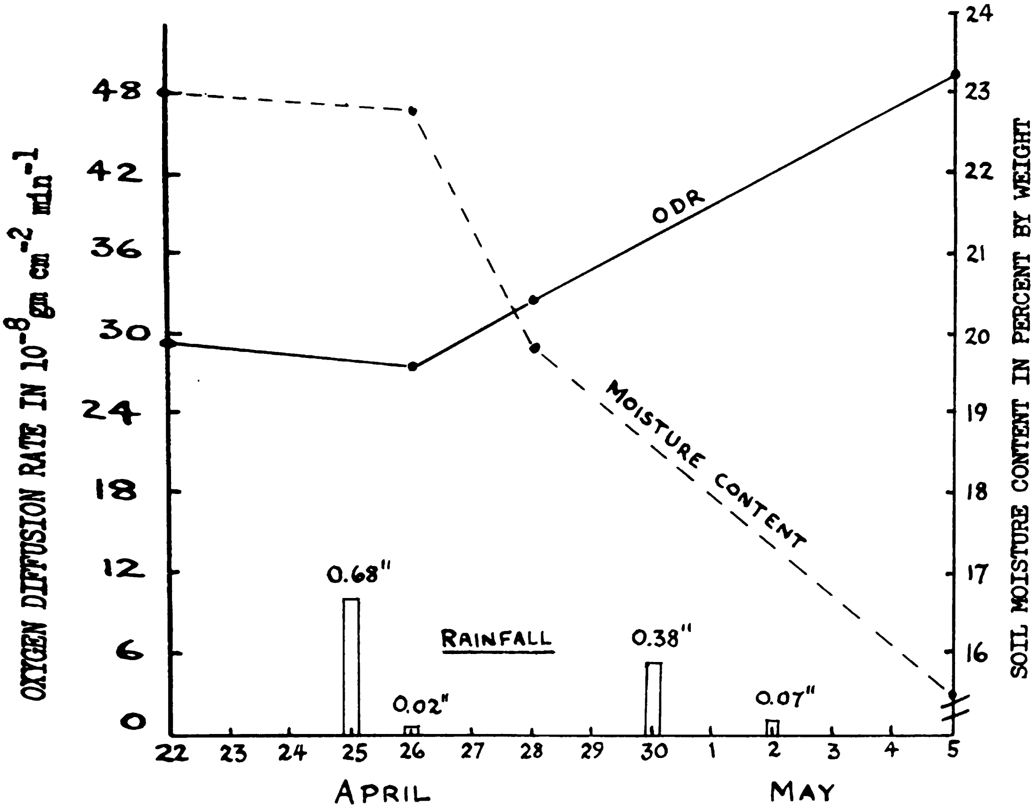


Figure 15. Change in Oxygen Diffusion Rate and Soil Moisture Content with Time at Farm Crops Farm.

thereafter. This is illustrated in Figure 9 based on similar data obtained at the Soil Science Farm. Figure 15 does, however, bring out very clearly the inverse relationship that exists between ODR and moisture content.

When the ODR and soil moisture content values are plotted against distance from the tile line, Figure 16 is obtained. The effect of the tile line on these properties of the soil is very significant. Thus, the ODR curves obtained for each of the dates on which measurements were made show very marked maximum values as they pass through the region directly over the tile line, while the corresponding soil moisture curves go through very distinct minimum values in the same region. The effects of distance to the tile line on such soil properties as color, firmness and consistency were also observed in the field when the measurements were made. The effects on color are seen in Figure 13 while on consistency were observed from the fact that it always required more pressure to insert the electrodes in the soil above the tile line than in other places in the field.

To determine more precisely the relationship which exists between the ODR and corresponding moisture content of the soil, Figure 17 was constructed, where the ODR values and corresponding soil moisture values measured at all points and dates were taken from Table C and plotted against one another. A linear relationship with a negative slope was obtained. The regression equation was $Y = 91.8 - 2.82\ X$ and was significant at the 1 percent level (the correlation coefficient was 0.926).

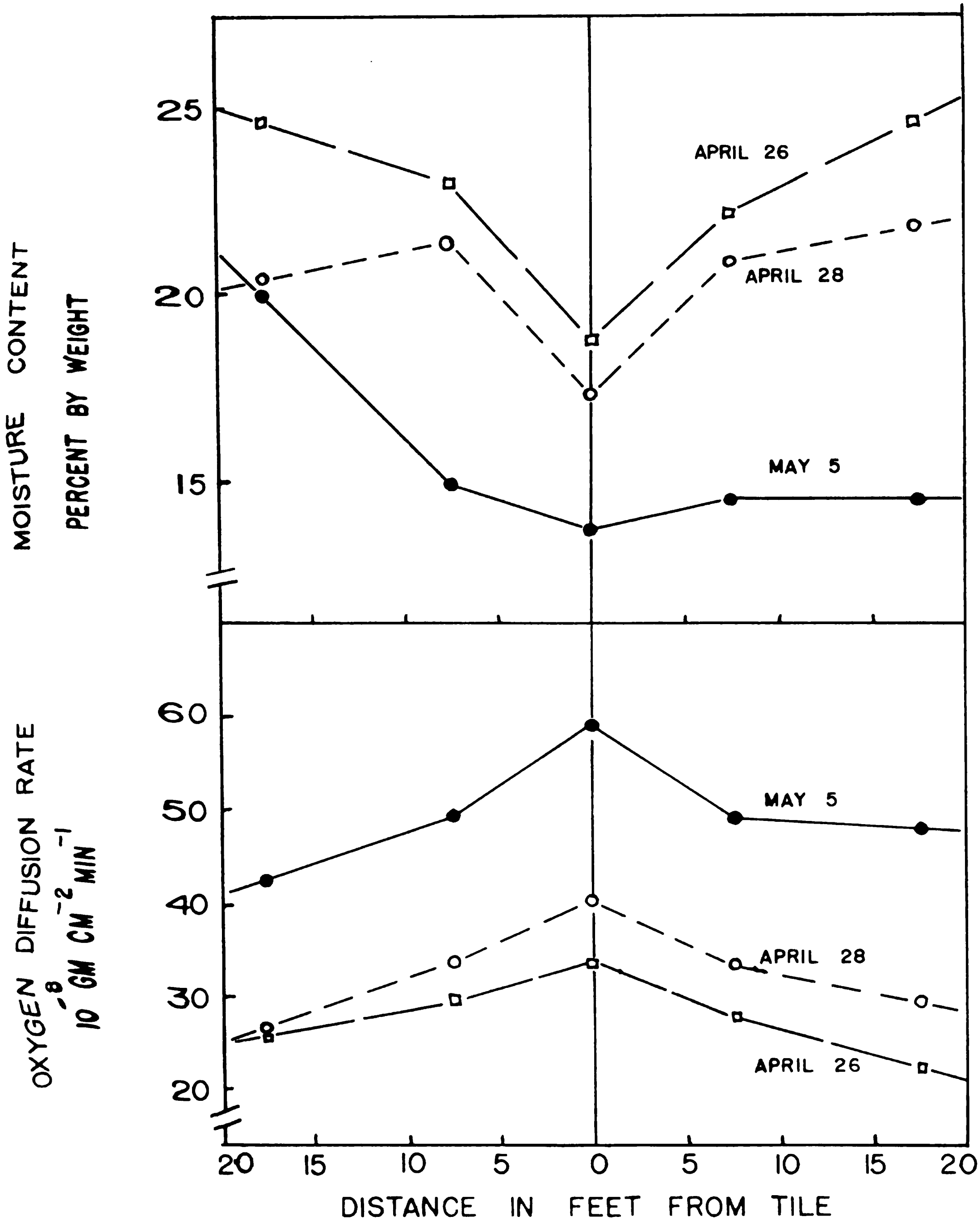


Figure 16. ODR values and Soil Moisture Contents measured at different dates and distances from the tile at Farm Crops Farm.

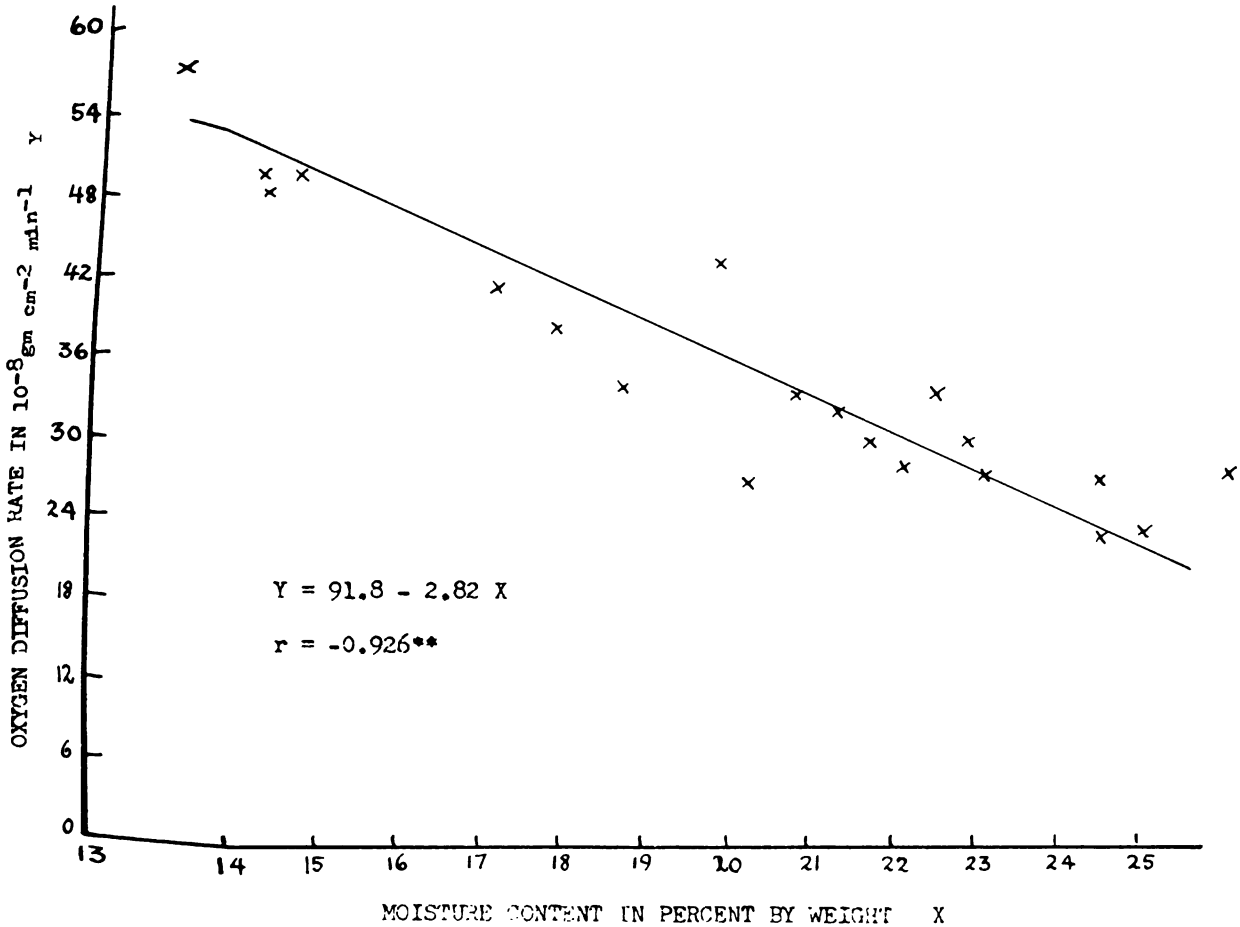


Figure 17. Plot of ODR versus Soil Moisture Content for data from Farm Crops Farm. (Conover loam)

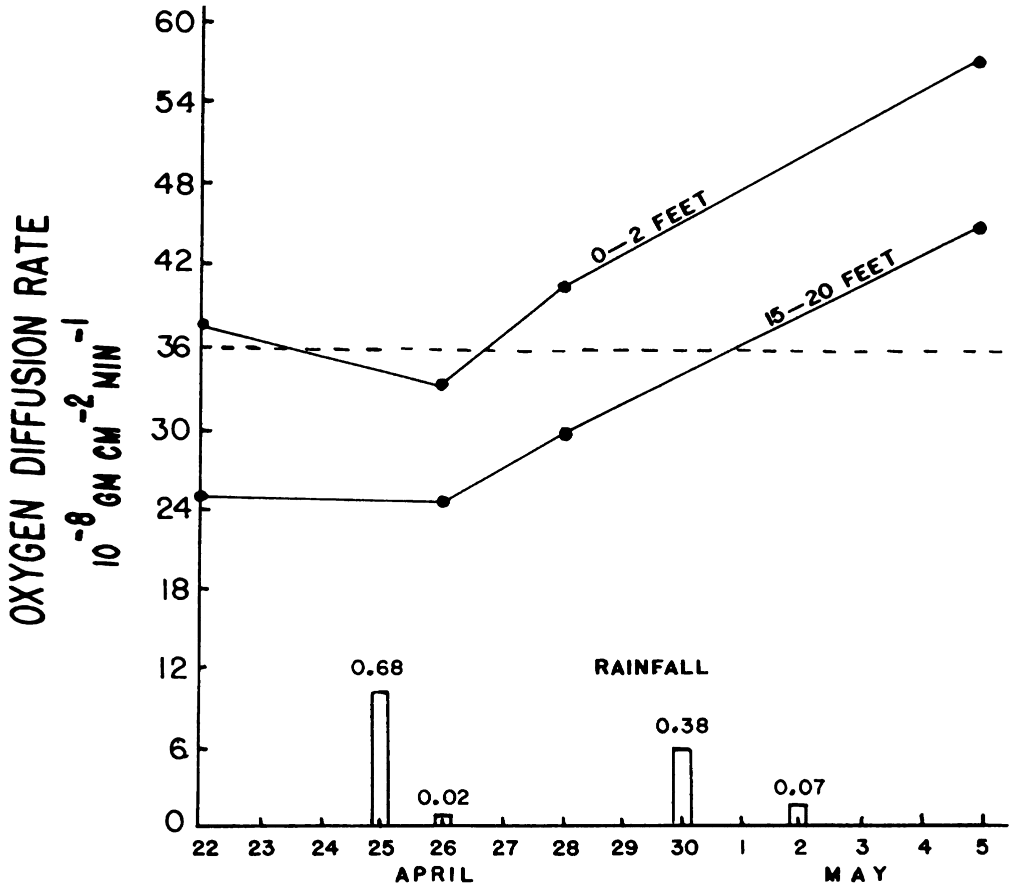


Figure 18. Diagram showing how the ODR values of the soil situated 0-2 and 15-20 feet from the tile vary with time over a two week period.

The importance of the intensity of drainage can be illustrated by plotting the average values of the ODR measured in the soil at 0-2 feet and 15-20 feet from the tile as a function of time, see Figure 18. This resembles Figure 15 except that a differentiation has been made between the well drained soil above the tile (0-2 feet) and the poorer drained soil 15-20 feet from the tile. If it is assumed that plants commonly require an oxygen supply at the rate of 36×10^{-8} O_2 cm^{-2} min^{-1}, it will be seen from Figure 18 that the soil at 0-2 feet will be oxygen deficient for only three days out of the total 13 days considered, while the soil 15-20 feet from the tile will be oxygen deficient from April 22 to May 1, or a period of 9 days. This three-fold reduction in the duration of the oxygen deficient period may greatly reduce the injury caused to plants and therefore be a very important aspect to consider in designing tile systems.

3. Summary

The ODR and moisture content values of the surface soil were very much influenced by the lateral distance from the tile line. For each date of measurement the ODR was at a maximum value immediately above the tile line, while the corresponding moisture content was at a minimum.

The combined effects of rainfall and drainage caused the ODR and moisture content to fluctuate in a cyclic fashion but in opposite directions (a displacement of half a period occurs due to their inverse relationship).

When poor drainage conditions (soil at 15-20 feet from tile) was compared with good drainage conditions (soil at 0-2 feet from tile) it was found that the difference could be expressed in terms of the length of time over which the soil was not able to supply a certain minimum ODR required by the plant roots. During the period April 22 to May 5, it was found that the 0-2 feet soil was not able to supply the assumed minimum ODR during 3 days while the 15-20 feet soil failed to supply this minimum during a period of 9 days out of the total 13 days.

A highly significant linear relationship was found between the ODR (Y value) and the corresponding moisture content (X value) and the regression equation was $Y = 91.8 - 2.82\ X$.

D. The Ferden Farm

1. Background

In 1940 the Soil Science Department of Michigan State University started an experiment at the Ferden Farm, situated in central Michigan, to study the effects of seven different crop rotations upon yields and soil structure. Some of the details and results of this experiment have been reported by Cook et al. 1945, Robertson 1955 and Van Doren 1958. Many interesting relationships have been found, but the points which are of special interest and significance to the present investigation are the following:

a) All the experimental plots are tile drained, the effect of which is very pronounced especially during the wet seasons of the year.

b) Crop yield and soil structure differences have been observed between the different rotation sequences used. As far as soil structure is concerned Robertson 1955 found that the soil under the cash crop rotation (rotation number 6, see below) was much less aggregated and less stable than the soil under any of the other six rotations tried. He also found that the soil porosity and percolation rate of water through the soil was lowest for rotation 6 and highest for the rotations containing sod crops, such as rotations 1 and 5 (see below). These two factors also correlated well with the crop yields obtained.

c) There are indications that the drainage of individual plots differs according to the rotations used on them. Thus Robertson 1955 observed that the soil under rotation 6 often drained more slowly

in the spring or after a rain than did the soil under any of the other rotations.

d) Soil aeration studies have previously been made on the different plots, using the microelectrode technique and the results have in most cases shown very good correlation with soil structure and yields. Thus Van Doren 1958 reports measurements of the ODR of the surface soil during the first month after planting of sugar beets for rotations 1 and 6 during the spring of 1955, 1956, and 1957. He found a marked relationship between the ODR values measured during this early period of the growing season and the final yields obtained. From this he concluded that poor soil structure or poor drainage, occuring early in the season when the plants are just getting established and have high oxygen requirements, can quite easily cause injuries, from which the plants never quite recover.

With these points in mind, plots from rotations 1, 3, 5, and 6 were selected for the present investigation, the main purpose of which was to study the drainage and aeration effects of the tile running through the plots and how these effects might be modified by the various crops and rotations being used.

2. Description of Site

The crop rotation experiment at the Ferden Farm, described in the previous section, is generally referred to as the Old Rotation Experiment. The four plots chosen from this for the present investigation are situated side by side in block 1 in the northeast corner of the

experiment field and are from north to south as follows (crop rotations in parenthesis):

Plot 6--Barley stubble (beans, wheat, corn, beets, barley)

Plot 5--Winter wheat (sweet clover, beans, beets, soybeans, wheat)

Plot 1--1st year alfalfa (alfalfa, alfalfa, corn, beets, barley)

Plot 3--Fall plowed (soybeans, wheat, beans, beets, corn)

Each plot is 28 x 90 feet in dimension and the land surface of all four plots is very even, varying only a little over one foot in height from the highest to the lowest point. A 4 inch tile runs down the middle of all four plots at a depth of a little over 2 feet. Forty feet to the east of the plots and parallel to the tile is an open ditch and 66 feet to the west of the tile and just outside the plots is another tile line belonging to the same drainage system. A map and cross section of the area is shown in Figure 19 and a photograph of plot 5 is seen in Figure 20.

The soil at the experimental site is classified as Sims clay loam and is a poorly drained Humic-Gley soil that occurs fairly commonly in level to depressed areas in central Michigan. The main problem with this soil is to obtain adequate outlets for artificial drainage systems that are necessary to make it suitable for intensive crop production. Under natural conditions the runoff and internal drainage of water are too slow for it to be very productive.

The weather history of the area prior to April 25, when the first measurements were made is as follows: A 10 inch deep snow layer covered the ground until March 26, when it began thawing and finally disappeared by April 1. Low precipitation and high evaporation during this period eliminated the usual spring flooding of the land. For this

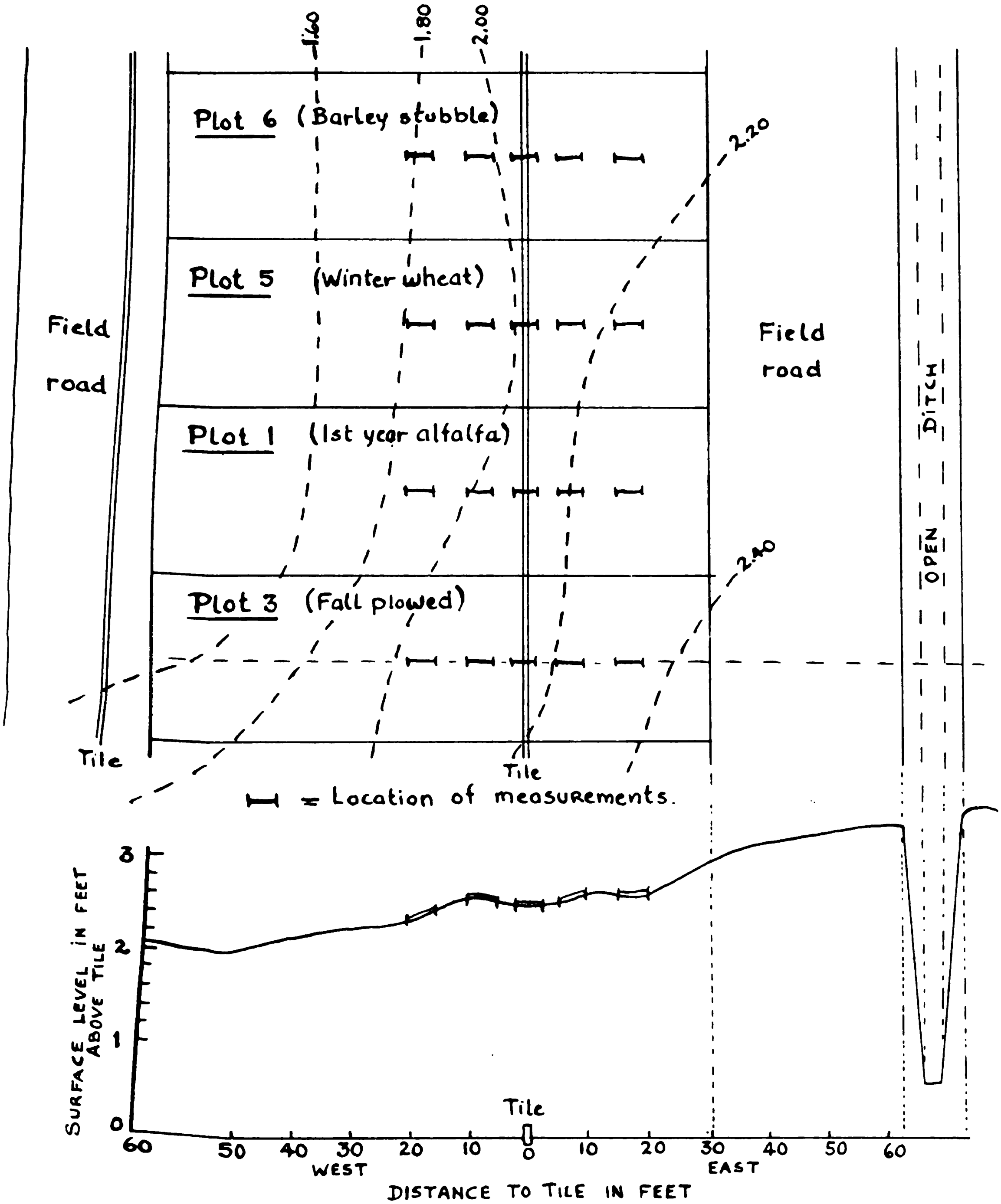


Figure 19. Map of the plots studied at the Ferden Farm and cross section of plot 3 showing land level and depth of tile.

Figure 20. Photograph taken April 28, 1960, looking east across plot 3 at the Ferden Farm. The crop is winter wheat.

reason measurements were postponed until rain came and put a stress on the drainage system. During April 24-25, 0.75 inches of rain fell followed by 0.52 inches on April 26. This rain was not sufficient to fully saturate the surface soil, but nevertheless oxygen diffusion measurements were begun on April 25 and continued until May 16. During this period 0.44 inches of rain fell on April 30 and 0.95 inches between May 6-10, as shown in Figure 23.

3. Results and Discussion

All the ODR and soil moisture content determinations made on the four plots are reported in Table D of the Appendix. Water table measurements were also made on plots 1 and 6 and the heights are given in Table E and shown graphically in Figure 21. Tensiometers were installed at 6 inch depths on these plots, but unfortunately had to be removed for other purposes before they began to register any moisture stress in the soil. Soil moisture retention curves were determined on the basis of core samples that were taken from all four plots and are shown in Figure 22. In Figure 23 the average ODR and moisture content values have been plotted according to the date and plot on which they were measured during the period April 25 to May 16, 1960. The top half of this figure shows how the ODR values varied and the lower half how the moisture contents varied during the period. When these are compared it will be seen how the ODR curves first go through a maximum on May 5 and then through a minimum on May 12, while the moisture curves proceed in exactly the opposite manner, passing first through a minimum on May 5

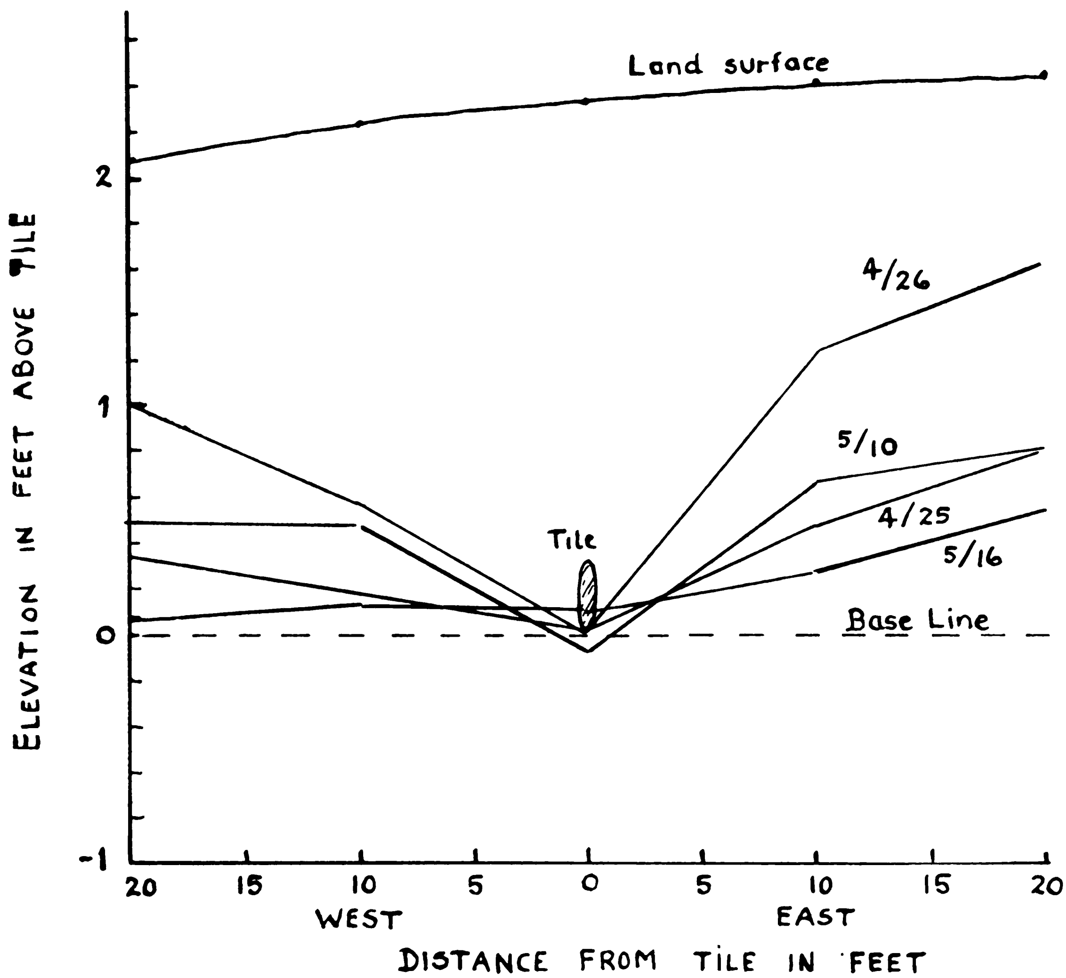


Figure 21. Height in feet of water table above drain tile for various dates on plot 6, Ferden Farm.

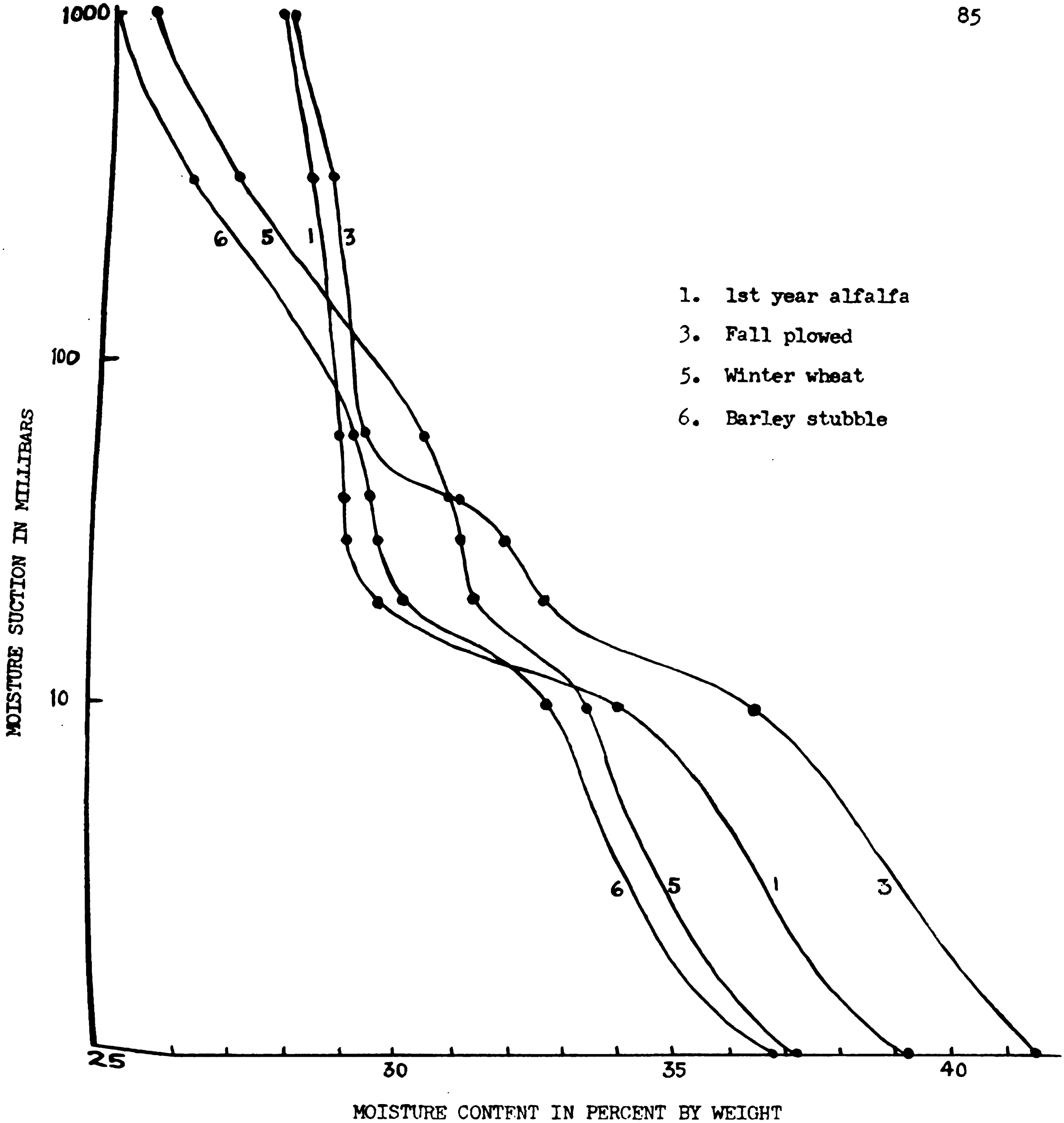


Figure 22. Moisture retention curves for Sims clay loam from plots in Old Rotation Experiment, Ferden Farm.

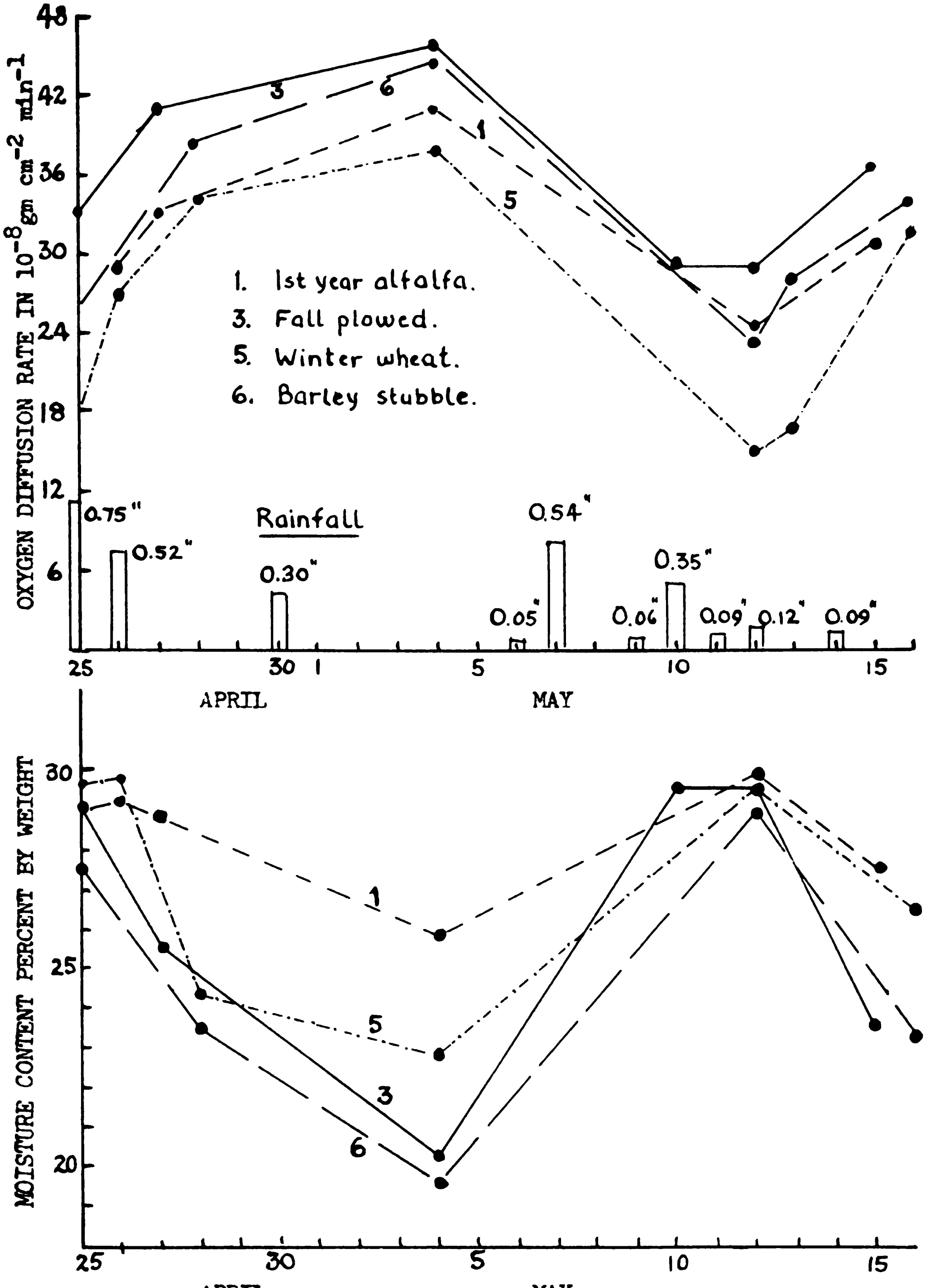


Figure 23. The variation in the average ODR and moisture content values of the soil on four plots at Ferden Farm during April 25 - May 16, 1960.

and then a maximum on May 12. The precipitation received is indicated by small columns, which correspond in height to the amount of rain received. Rainfall and drainage are the factors which govern the fluctuations in the ODR and moisture content values.

In Figure 23 it is also possible to compare the differences in the aeration and moisture conditions that occurred between plots. These differences will depend partly on the differences in the present year's cropping of the plots and partly on the previous year's cropping practices (crop rotations). From page 80 it will be seen that plots 1 and 6 have had identical crops grown on them for the last three seasons (corn 1957, beets 1958 and barley 1959). The only difference between these plots is that in 1959 barley was seeded alone on plot 6 while it was seeded with alfalfa on plot 1. Figure 23 shows that throughout the period April 25 to May 16 the ODR for plot 6 was higher than plot 1 and that the corresponding moisture content was lower. From Figure 22 it will also be seen that the moisture retention curve for the soil from plot 6 is lower than that for plot 1 (except for suctions between 10-100 millibars, where they are very similar). Although the differences are not very great, these results seem to indicate that the soil structure on plot 6 was better than on plot 1 as far as drainage and subsequent aeration is concerned. This is in conflict with the findings of Robertson 1955, who reported that the soil structure was more deteriorated by the cash crop rotation used on plot 6 than by any of the rotations used on the other plots. The studies made by the author were, however, carried out so early in the season that deterioration of soil structure probably had not yet had time to occur and the results were therefore reflecting the beneficial effects of winter frost action on soil structure rather than the effects of different crop rotations and management practices used.

When the ODR curves for all plots are compared in the upper half of Figure 23, it will be seen that these maintain the same order throughout the period studied. The order is from highest to lowest plot 3 (fall plowed), plot 6 (barley stubble), plot 1 (first year alfalfa) and plot 5 (winter wheat). That the fall plowed soil gave the highest ODR throughout the period is almost to be expected, since plowing causes an increase in the porosity and drainability of the surface soil. That the ODR of the soil on plot 6 (barley stubble) should be better than that of plot 1 (alfalfa) or plot 5 (winter wheat) is in conflict with the findings of previous investigators, but may as before mentioned, be due to the dominating effect of winter frost action on soil structure early in the season, rather than the effect of the different crops.

When the moisture curves are similarly compared in the lower half of Figure 23, it will be seen that the curves are less consistent than those for the ODR, and that the general order from lowest to highest moisture content is plot 6, 3, 5 and 1. This is different from the order obtained for the ODR curves, since plots 6 and 3 and also 5 and 1 here appear in reverse order. When the moisture retention curves are compared in Figure 22, a third order in the general magnitudes of the soil drainage properties of the plots is found. These discrepancies in the physical properties of the soil probably depend on both errors made in the sampling and measurement of the soil as well as the dynamic nature of it during the spring, when its structure is undergoing readjustments after the freezing and thawing action of the winter season.

In Figures 24 to 27, the ODR and moisture content values of the surface soil determined on each plot are graphed as a function of the lateral distance to the tile line. These figures indicate that there was very little if any drainage effect of the tile. The dotted curve in each diagram is the calculated average of all the other curves drawn and has been constructed to help point out any drainage effects that may exist. Only for plot 5 (winter wheat) is there any significant indication of a drainage effect of the tile. From the moisture diagrams, it will be noticed that almost all the curves are below the 30 percent moisture content value. In Figure 22 where the moisture retention curves for each plot is given, it will be seen that very high tensions have to be applied to remove moisture below the 30 percent value. Since the maximum suction that can be exerted by the tile is less than 80 cm, it is obvious that there cannot be any drainage effect unless the soil is initially at moisture contents above 30 percent by weight. Since the moisture content was below this value throughout the period studied, this would explain why no drainage effect was observed.

In Figure 28 a graph has been made of the average ODR values versus the corresponding average moisture contents of the soil. A simple correlation analysis was also made to find the straight line that best fitted the points plotted. The regression equation found was $Y = 109.6 - 2.94 X$, where Y is the ODR value in $10^{-8} \times$ gm O_2 cm^{-2} min^{-1} and X is the moisture content in percent by weight. This equation was significant at the one percent level with a correlation coefficient of 0.823.

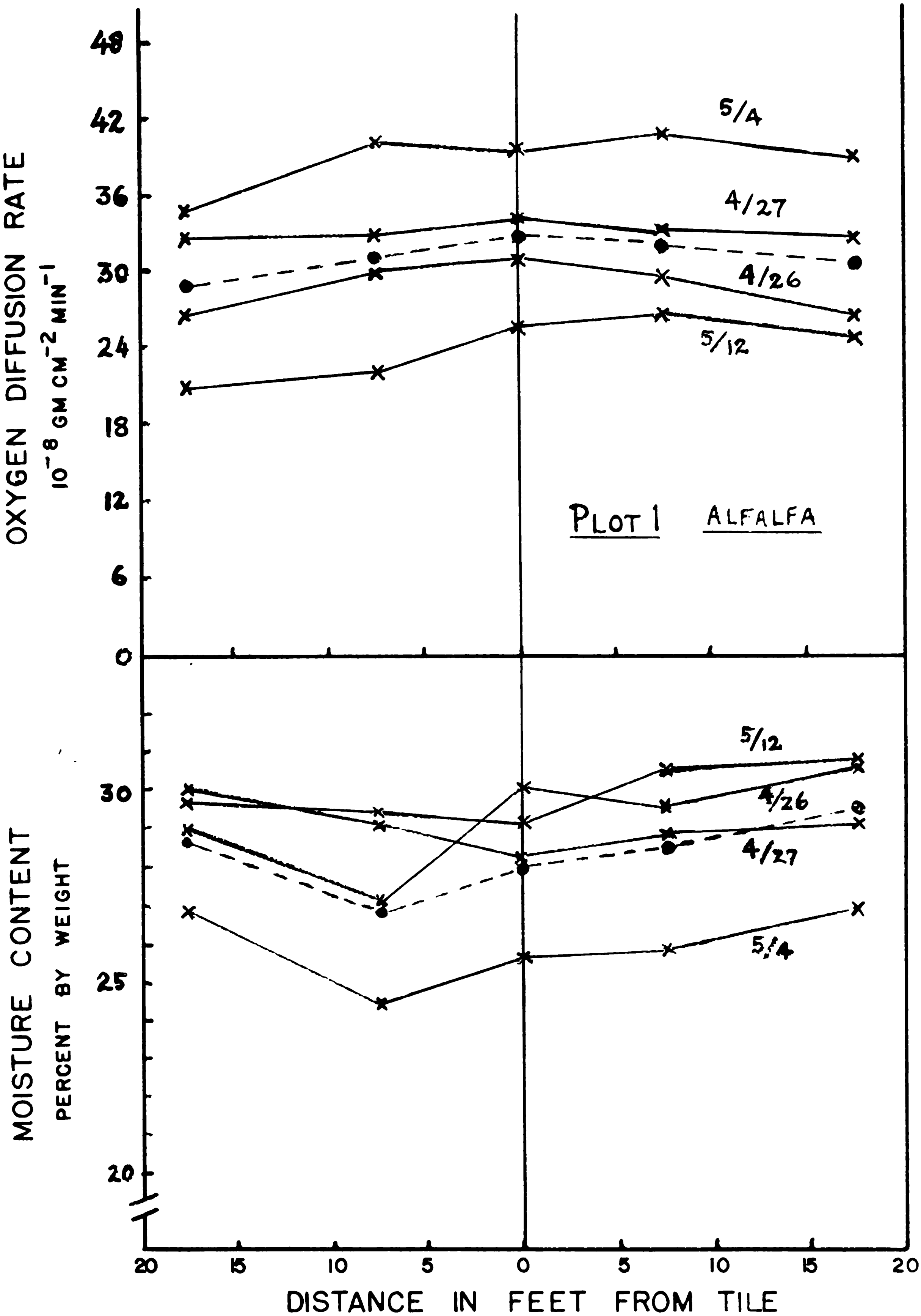


Figure 24. The ODR and moisture content of the surface soil measured at different dates and distances from the tile on plot 1, Ferden Farm.

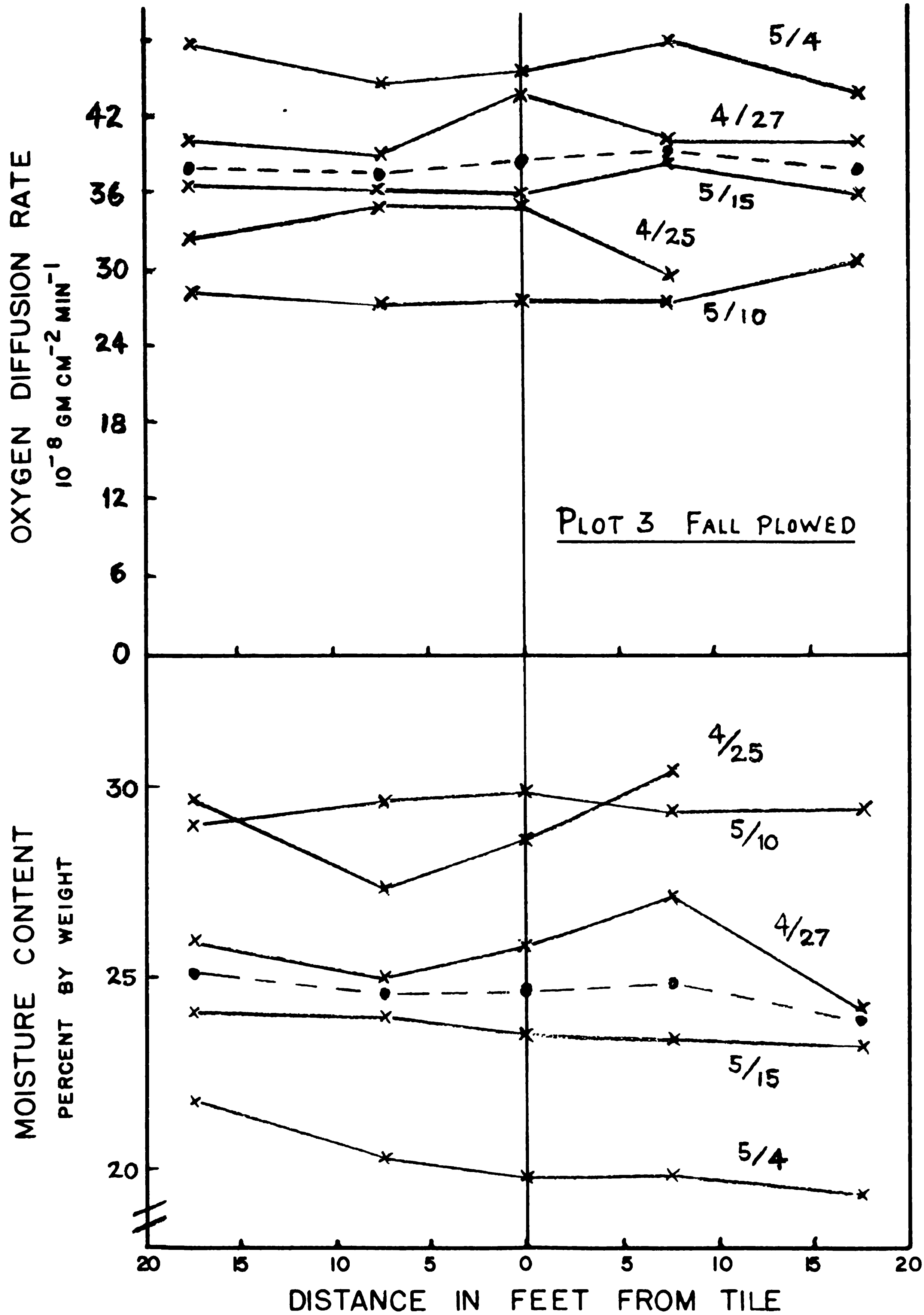


Figure 25. The ODR and moisture content of the surface soil measured at different dates and distances from the tile on plot 3, Ferden Farm.

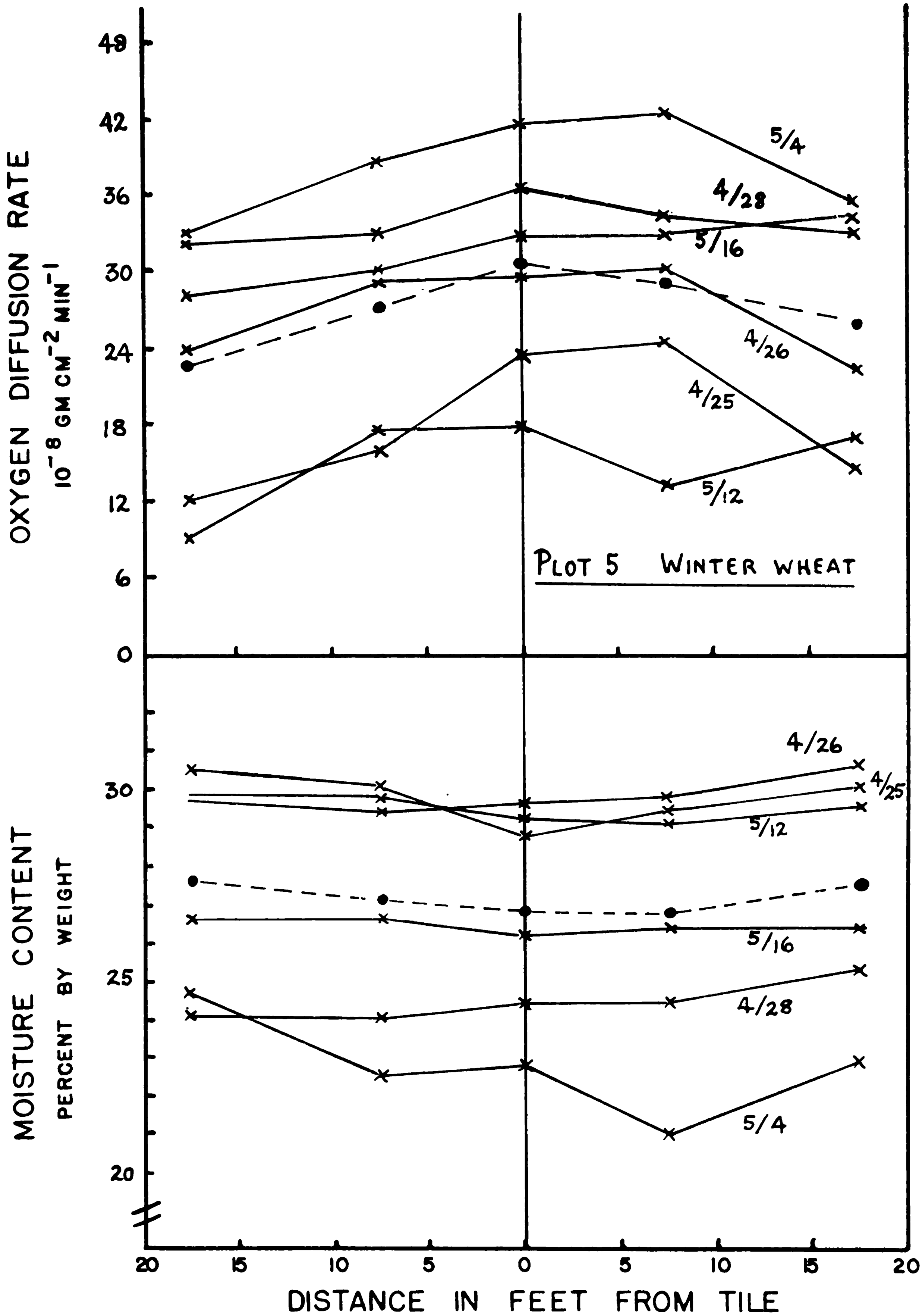


Figure 26. The ODR and moisture content of the surface soil measured at different dates and distances from the tile on plot 5, Ferden Farm.

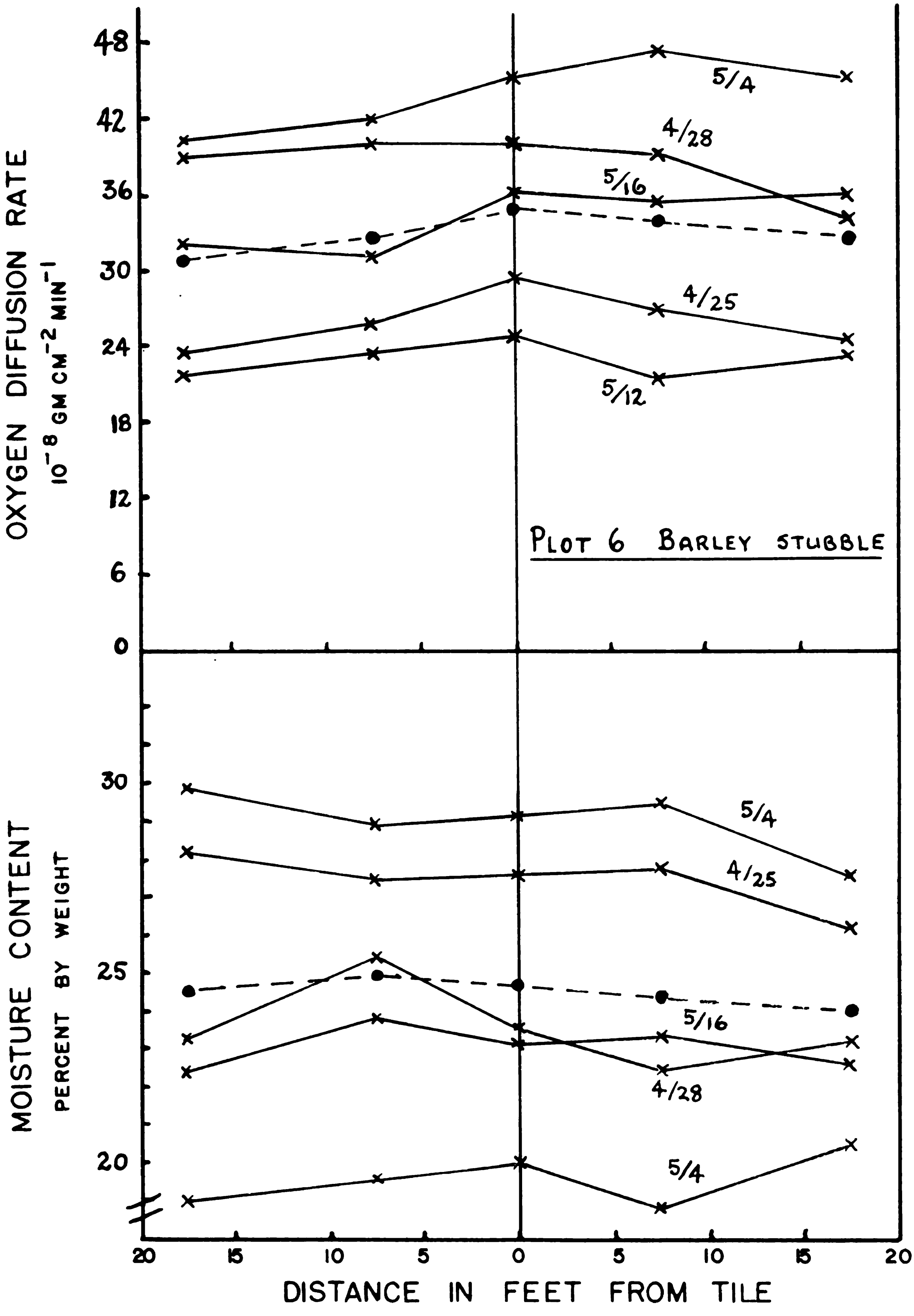


Figure 27. The ODR and moisture content of the surface soil measured at different dates and distances from the tile on plot 6, Ferden Farm.

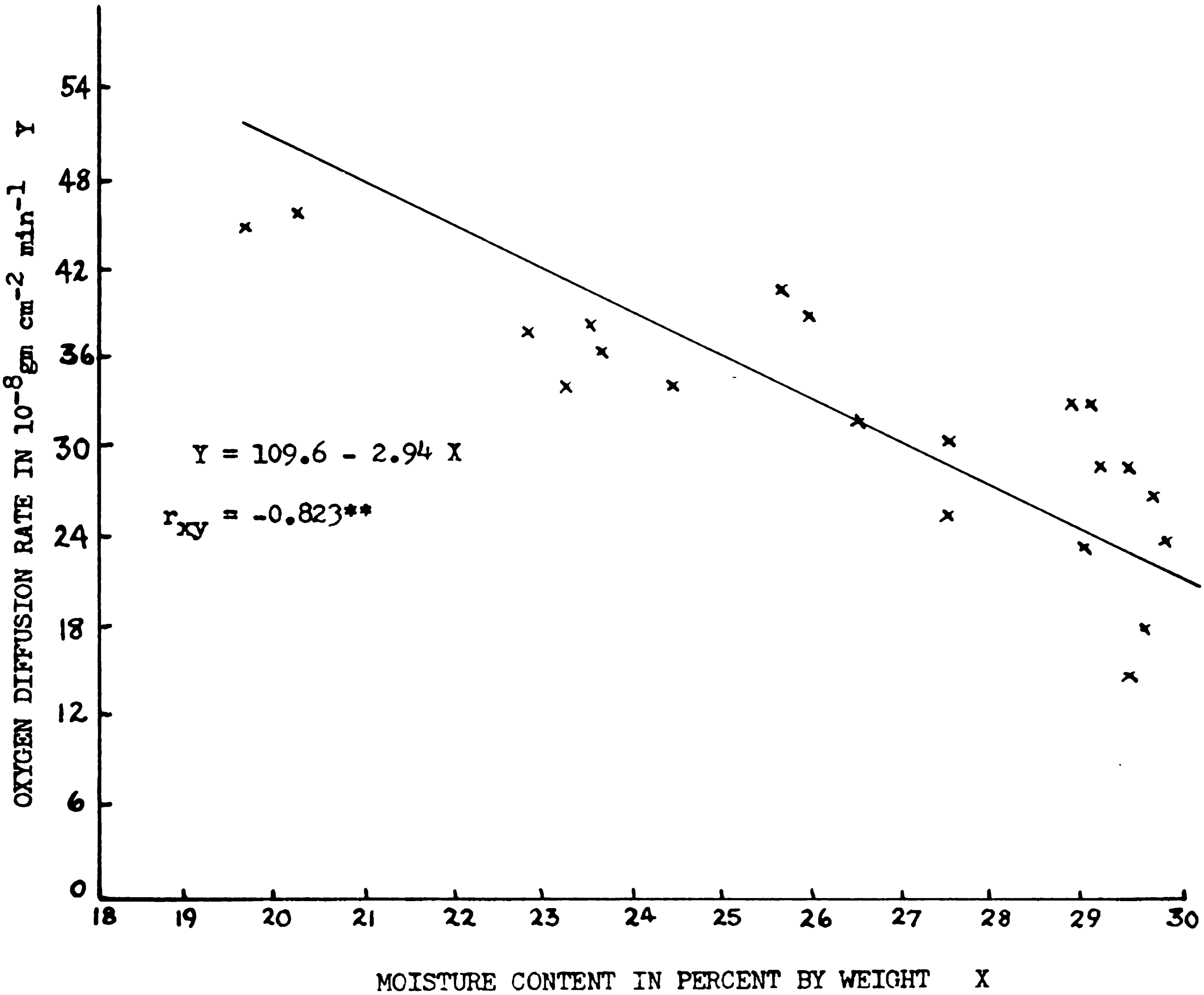


Figure 28. Plot of ODR versus moisture content data from Ferden Farm (Sims clay loam).

4. Summary

ODR and moisture content measurements were made on four plots chosen from the Old Rotation Experiment at Ferden Farm during April 25 to May 16, 1960. The average ODR values determined for each observation date and plot showed that the fall plowed plot (3) had the highest value throughout the period studied and that it was followed by the other plots in the order, barley stubble plot (6), first year alfalfa plot (1) and winter wheat plot (5). The average moisture content values for the plots did not exactly follow this order, but showed that the barley stubble plot (6) was driest followed by plots 3, 5 and 1. The differences between the plots were not very great and the discrepancies observed probably depended mainly on the unstable and variable nature of the soil in the spring after the frost action of the winter season.

Little if any drainage effect of the tile was observed from the ODR and moisture content values determined at various distances lateral to the tile. From the moisture retention curves for the soils on each of the plots, it was seen that the conditions were too dry in the surface soil of the plots during the period studied for the tile to be able to extract any water.

A linear relationship was found between the ODR and corresponding moisture content values that was highly significant, the regression equation being $Y = 109.6 - 2.94\ X$.

E. The Crawford Farm

1. Description of Site

During May 19-20 measurements of the ODR and moisture content of the surface soil were made at the Crawford Farm, situated 12 miles south of Sault Ste. Marie and 3 miles east of Dafter in Michigan's Upper Peninsula. On this farm is located the Chippewa County Drainage Project, which covers 12 acres of land, where bedding, mole and tile drainage have been compared since their installation in 1951, see King et al. 1959. The field is divided into four cropping areas with the drainage treatments running through all four of these. In the Spring of 1960 the crops grown in these areas were from east to west:

A. First year hay

B. Fall plowed

C. Second year hay

D. Winter wheat

The layout of this field and the areas where the studies were made are shown in Figure 29. A photograph of part of the area is shown in Figure 30.

The soil where the measurements were made is classified as a Pickford clay and is characterized by its poor drainage conditions, due to both low permeability of the soil and poor outlet conditions from the area. The farmers of Chippewa County try to overcome the drainage problem of this and similar soils by the method of plowing their fields in narrow beds where the dead furrows are left as surface drains. Even with this method the water often remains in the dead furrows until late May.

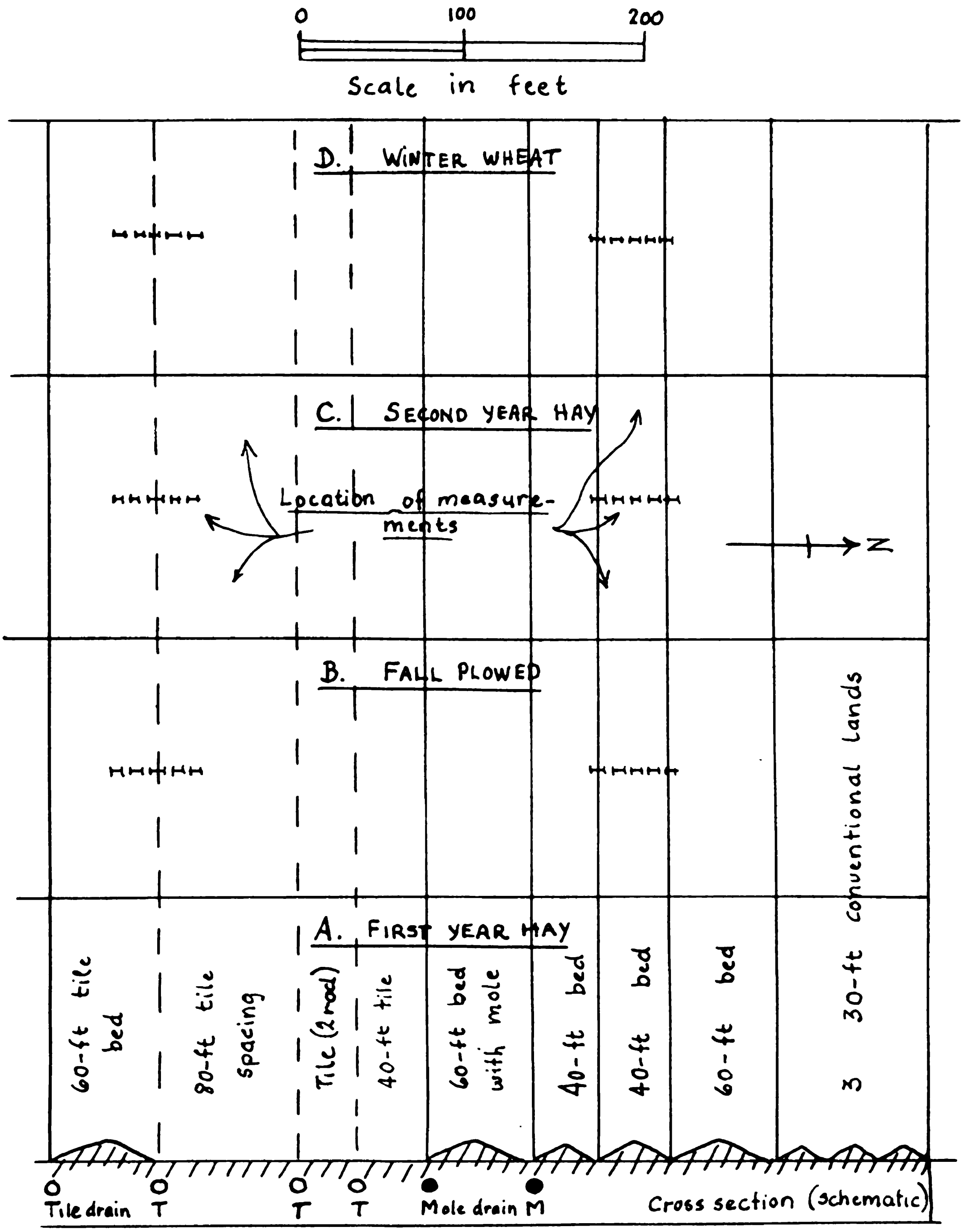


Figure 29. Map of northern half of the Chippewa County Drainage Project at Crawford Farm, showing the drainage systems and location of measurements.

Figure 30. Part of area D at the Crawford Farm, which is laid as a 40 feet wide untiled bed for removal of surface water. Notice the poor growth of winter wheat in the dead furrows at either sides of the photograph, which was taken May 20, 1960.

The use of tile drainage to improve conditions has proven very successful on the Crawford Farm. The tiled plots there have yielded more wheat, oats and hay than the conventional untiled beds. In Table G some data taken from an investigation by King et al. 1959 have been compiled to show the differences in crop yields measured on the tiled and bedded land. The yields were in this case measured at distances of 0-8, 8-16, and 16-20 feet from the tile or bed ridge to determine the effects of these. Figure 31 shows how the oat and wheat yields obtained vary with distance from the tile or bed ridge. The yield curves for the tiled land are also seen to be far higher and more even than those for the bedded land, which decrease considerably as the distance from the bed ridge exceeds 12 feet. The same investigators also reported that the botanical composition of the hay differed between untiled and tiled land and that more alfalfa and less ladino clover was found in the tiled than the bedded land especially for the second year crop.

The time chosen for the measurements could hardly have been better selected as far as the weather conditions were concerned. April had been a cold and wet month with precipitation almost every day. The last traces of the snow cover disappeared on April 20, but the frost probably did not leave the ground until the first week in May. During the first ten days of May it rained every day giving a total precipitation of 4.74 inches for this period. Then followed 9 days of dry and also warmer weather. However, on May 19 surface water still remained in the dead furrows of the untiled land, and the ditches and tiles were still running. Attempts at measuring the height of the water table were

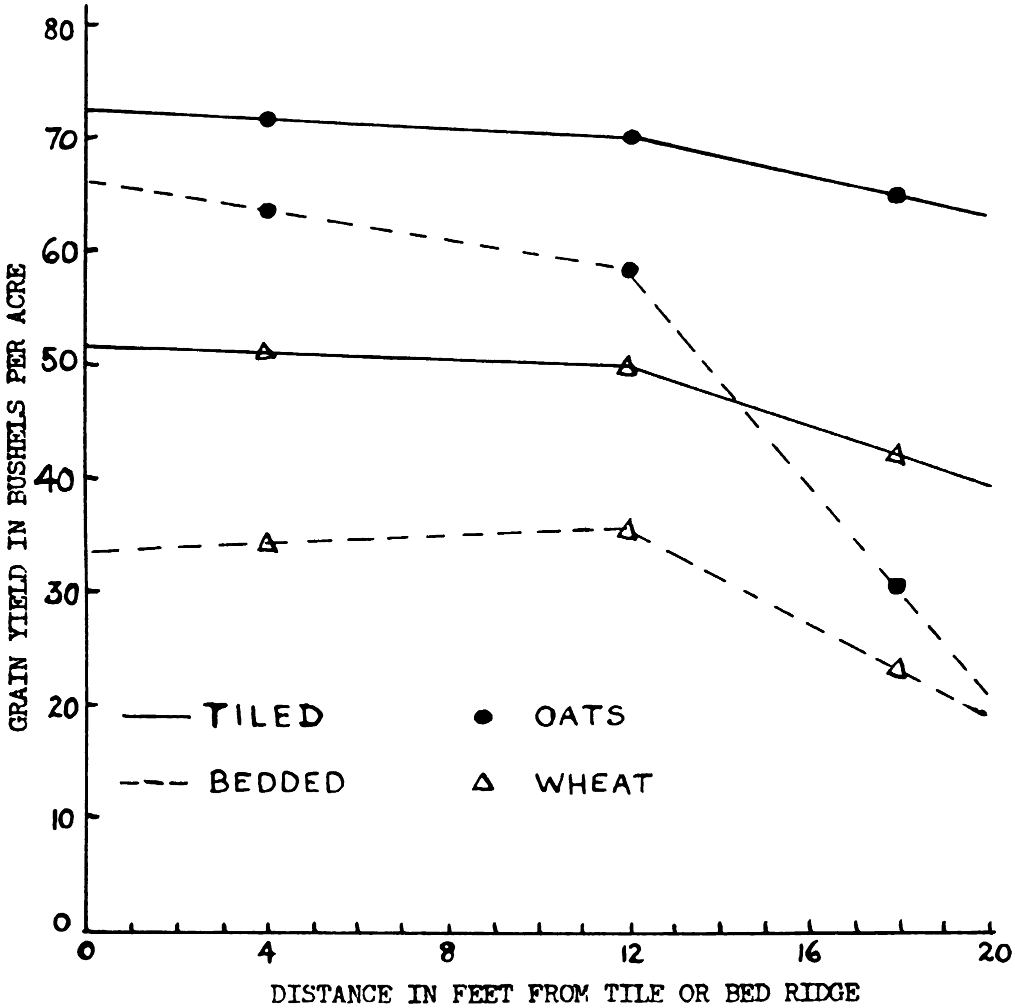


Figure 31. The yield of oats and wheat measured at different distances from the tile or bed ridge at the Chippewa County Drainage Project, Crawford Farm (from King et al. 1959).

made using wells, but the hydraulic conductivity and drainability of the soil were too low to give any reliable results. The effects of the various drainage systems on the field were quite apparent in the color and consistency of the soil.

2. Results and Discussion

Soil core samples were taken from both the tiled and bedded land where winter wheat was grown (area D) and the moisture retention data determined in the laboratory from these are shown graphically in Figure 32. It is very interesting to note from this figure, that the soil from both drainage areas holds about the same amount of moisture at the saturation point, but that as the suction exceeds 20 millibars, the tiled soil loses much more water than the soil from the bedded area. This indicates that there must also be a significant difference in the structure of the soil in the two areas.

In Figure 33 the ODR and moisture content values that were determined across the tile and bed for the various cropping areas are shown. The values are also given in Table F in the Appendix. From the figure it is clearly seen that the drainage effect of the tile is far greater than that of the bedding. Even at a distance of 20 feet from the tile line the soil was generally drier and gave higher ODR values than the soil at the ridge of the untiled bed. The average ODR value for all the tiled land was 27×10^{-8} gm O_2 cm^{-2} min^{-1}. This was more than twice that measured on the bedded land, which was 11×10^{-8} gm O_2 cm^{-2} min^{-1}. The corresponding average moisture content of the tiled land was 28.8% as compared with 36.5% on the bedded land.

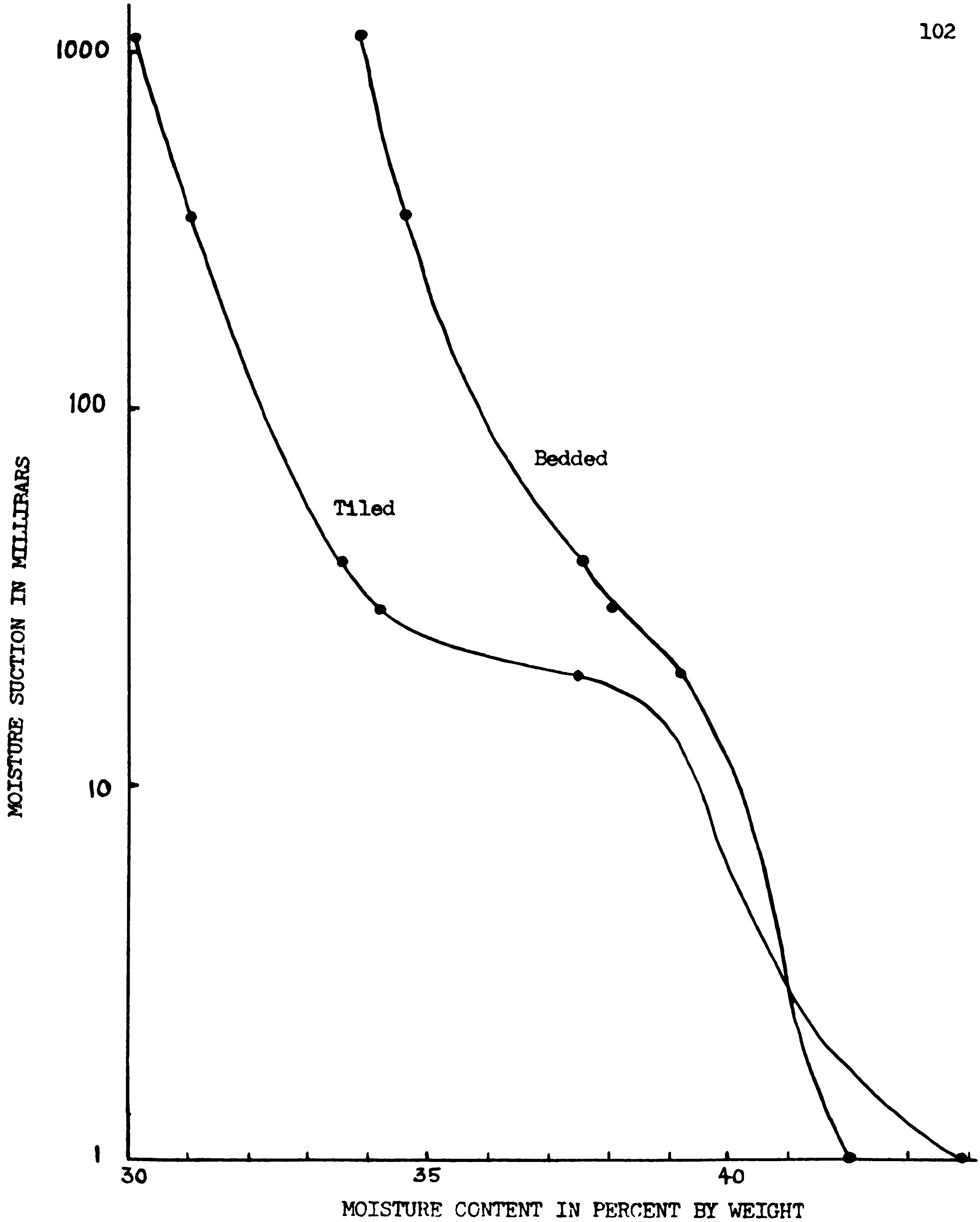


Figure 32. Moisture retention curves for Pickford clay from the Crawford Farm.

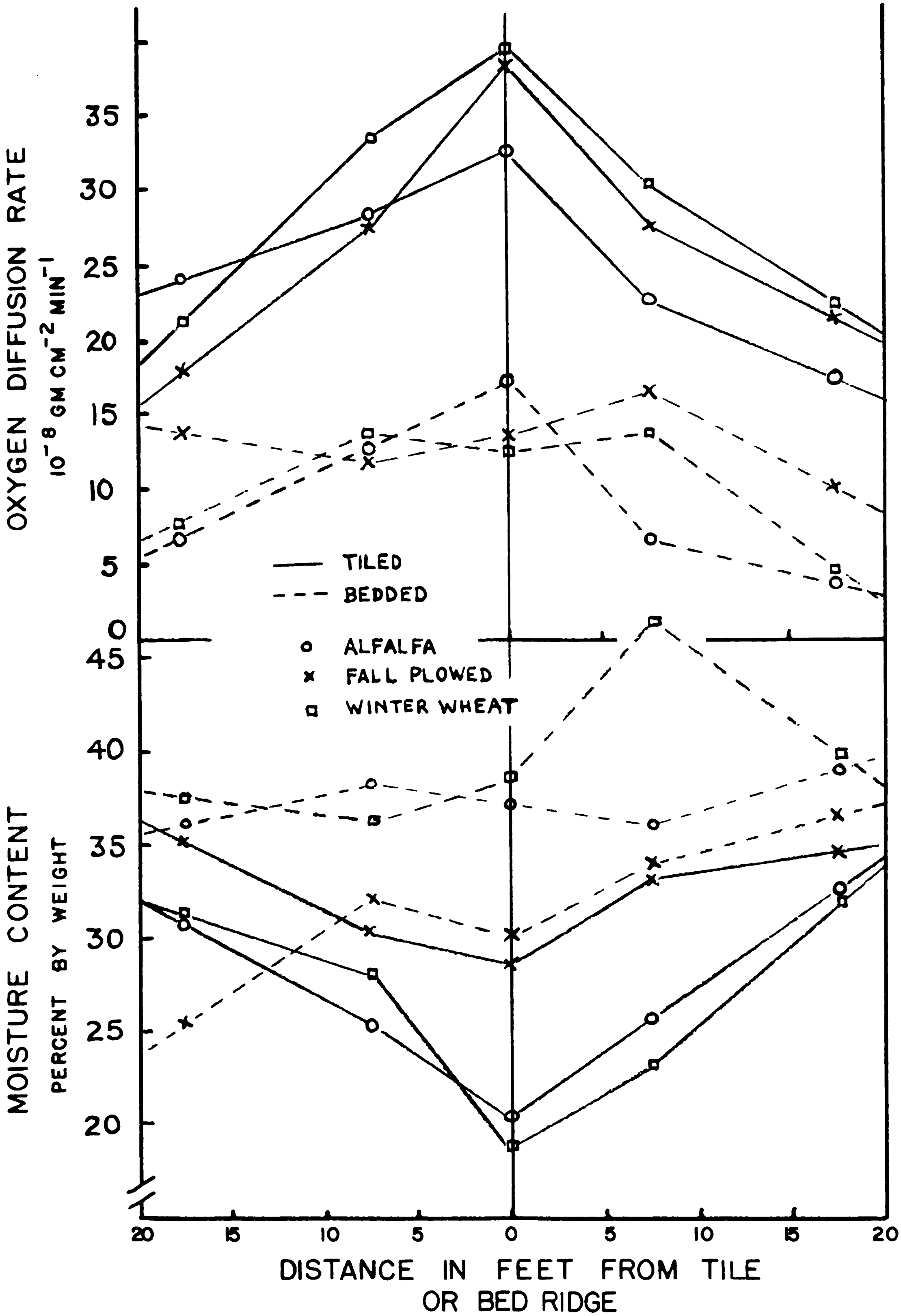


Figure 33. The ODR and moisture content of the surface soil measured across a tile line and bed ridge at Crawford Farm, May 19-20, 1960.

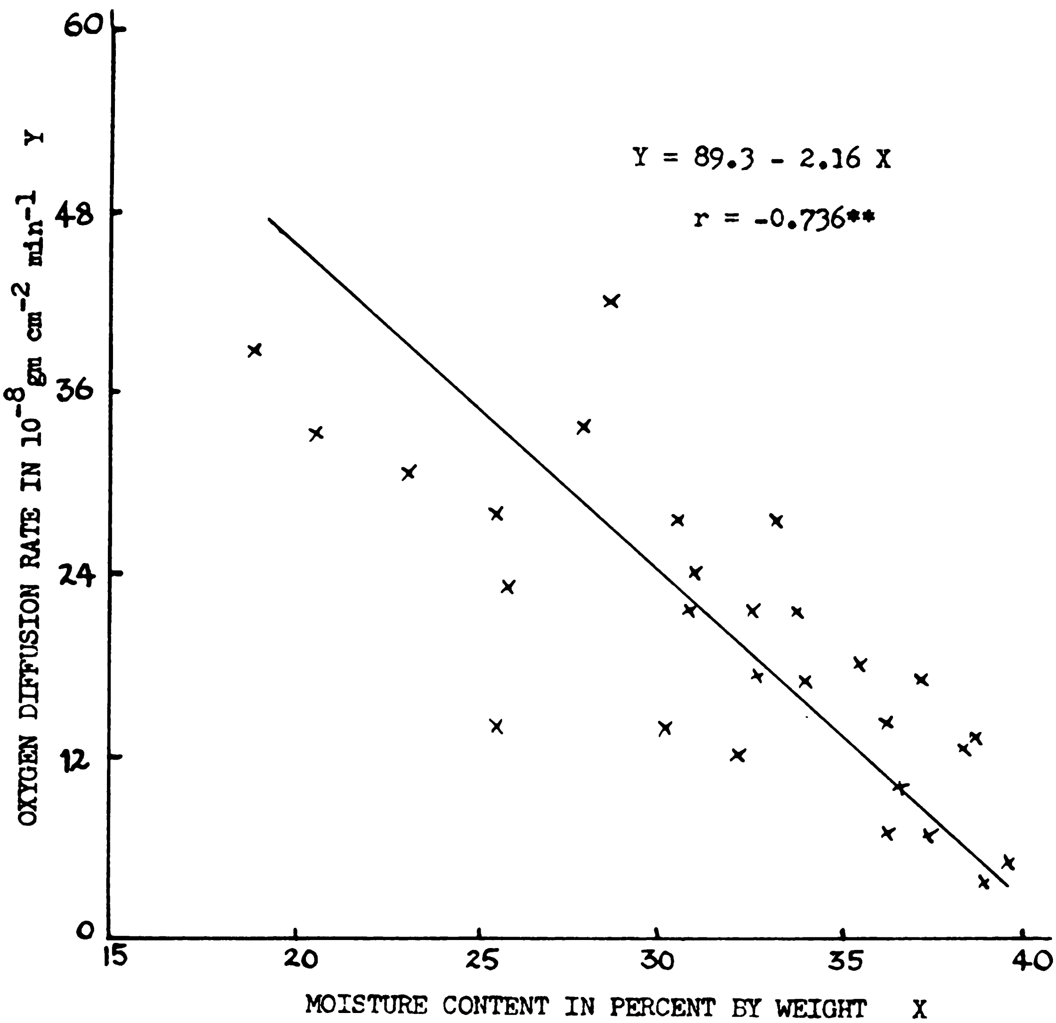


Figure 34. Plot of the ODR versus soil moisture content data from Crawford Farm (Pickford clay).

Taking all the data from both the tiled and untiled land, the relationship between soil moisture content in percent by weight and corresponding ODR in 10^{-8} gm O_2 cm^{-2} min^{-1} was studied, see Figure 34. Simple correlation analysis gave the straight line $Y = 89.3 - 2.16 X$, which had a correlation coefficient of 0.736, that was significant at the 1 percent level.

3. Summary

Tiling was far better than bedding in establishing high ODR conditions and removing excess moisture. The average ODR value for the tiled land was more than twice that of the bedded land while the average moisture content was about 25% lower than that of the bedded land.

There was a marked effect of the distance to the tile line on the ODR and moisture content of the soil. Thus the ODR measured 0-2 feet from the tile was almost twice as high as that measured 15-20 feet from the tile. The relative difference in moisture content between these two distances from the tile was not as high, but nevertheless very significant.

For the bedded land the ODR increased markedly towards the bed ridge while the moisture content decreased only slightly.

The effects of distance to the tile or bed ridge on the ODR and moisture content compared very well with the crop yields reported by King et al. in 1959, which were also measured in relation to the position of the tile or bed ridge.

The regression equation between the ODR (Y value) and corresponding moisture content (X value) was $Y = 89.3 - 2.16\ X$ and the correlation coefficient was significant at the one percent level (0.736).

F. The North Central Substation of the Ohio Agricultural Experiment Station

1. Description of Site

The North Central Ohio Substation is situated seven miles west of Sandusky and five miles northwest of Castalia in northern Ohio. Originally the land in this area was marsh, which has been cleared and drained to make cultivation possible. Drainage is still the major factor limiting full-scale production of the land. There are three main reasons for this. One is that the land is extremely level, being located on an old glacial lakebed, which offers very poor conditions for surface water runoff. The second is that the level of the land is only a few feet above the level of the water in Lake Erie, which is the nearest outlet, thereby limiting the use of tile drainage, unless pumping is used, as is the case at the Substation. Finally, the very low hydraulic conductivity of the soil constitutes the third reason why satisfactory drainage is difficult to achieve in the area.

The soil at the experimental site is classified as Toledo silty clay and is a very poorly drained Humic-Gley. It contains about 50% clay and more than 40% silt throughout the profile. A study of the drainage conditions and the characteristics of water removal from the soil has been reported by Taylor and Goins 1957. They found that the hydraulic conductivity, although low in the whole of the soil profile, was considerably higher in the A than the B horizon. During the course of drainage, the water removal from the A horizon was also found to be both greater and more rapid than from the B, where it was thought that deep seepage might account for some of the water removal. Although the conductivity of the A horizon was more than 50 times greater than that of the B, the authors were of the opinion that the depth of the A horizon was too shallow (8 inches) to permit significant water removal by lateral flow to the backfill. Also they state that, "considering the slow rate at which the water table is lowered in the B horizon as well as the small amount of porosity which is emptied in that soil region, one might conclude that tile drainage does not greatly improve aeration below the 12-inch depth."

2. Experimental Design and Methods

In 1957 a special experiment was designed on one of the fields at the Substation for the purpose of studying the relative effects of various drainage treatments on crop growth and soil physical conditions. Four different drainage treatments replicated four times were chosen as follows:

Treatment A No drainage

B Surface drainage only

C Tile drainage only

D Tile and surface drainage combined.

The layout of the drainage system and the location of the four treatments in each of the four replications is shown in Figure 35. All plots are 120 x 200 feet in dimension and surrounded by a 6 inch high earth dike

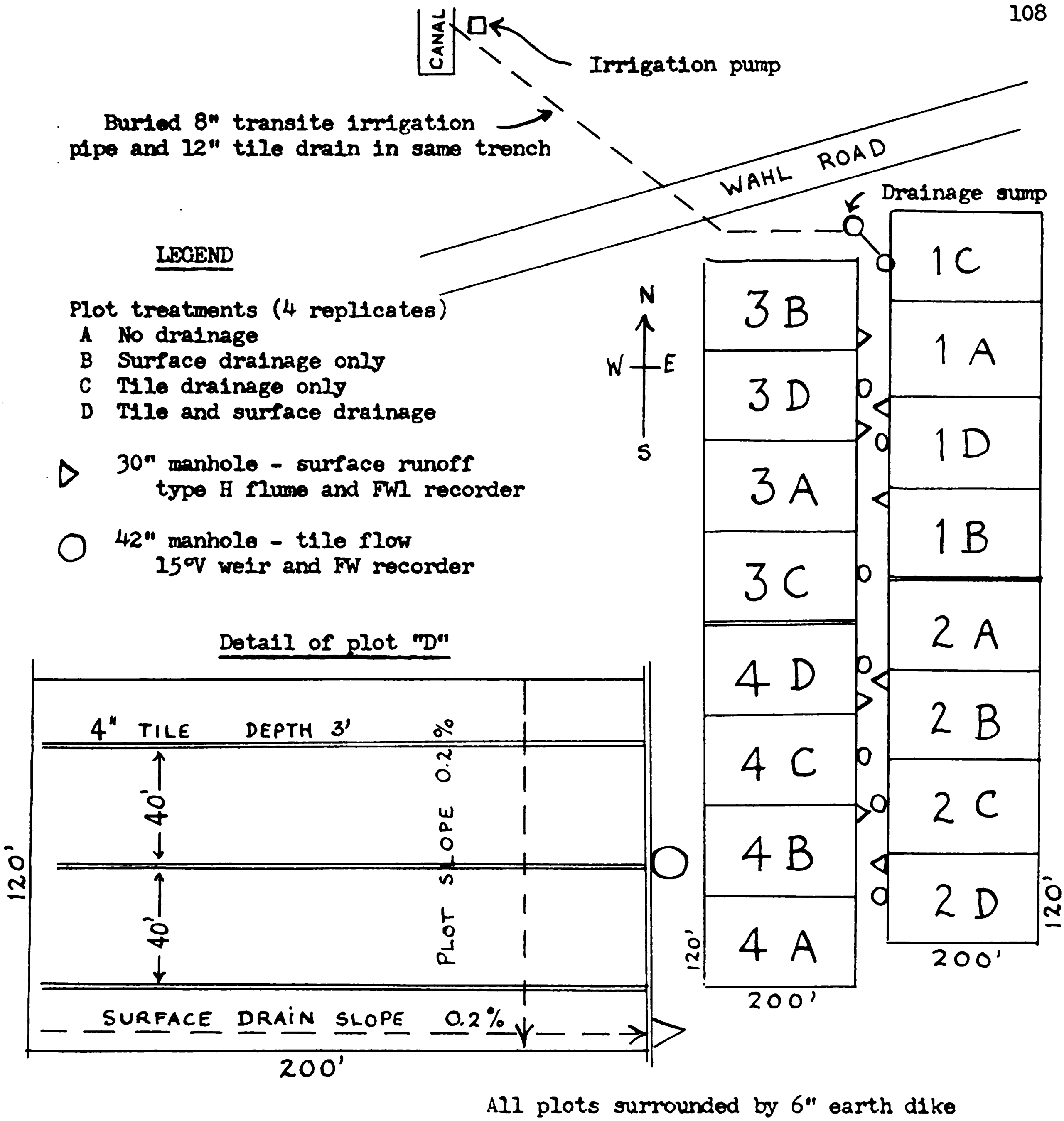


Figure 35. Plan of Tile-Surface Drainage Experiment at the North Central Substation of the Ohio Agricultural Experiment Station.

to prevent surface water from running between the plots. The surface of the A plots (no drainage) was kept as level as possible, whereas the B plots (surface drainage only) were graded slightly (0.2% slope) to one side, where a shallow open ditch was provided to collect the surface water and lead this to a 30 inch manhole containing a Type H flume and an FW-1 recorder to measure the amount of surface water runoff. The C plots (tile drainage only) were kept level at the surface but installed with three 4 inch tile lines at a depth of 3 feet and a spacing of 40 feet. All three of these tile lines were connected to a 42 inch manhole containing a V-notch weir and a FW-1 water stage recorder to measure tile flow. The D plots (tile and surface drainage combined) were made to include the features of both the B and C plots. An irrigation system was also installed, so that water could be applied to the plots to provide soil moisture conditions as desired. The project was called the Tile-Surface Drainage Experiment, to which it will also be referred in the following.

On September 12, 1960, a special study was begun at the site to see how the various drainage treatments would compare in their effects to remove the water from a 4 inch irrigation application. One replication was irrigated each night beginning with replication 1 on the night of September 12-13. Precisely 3.9 inches of water was applied to each replication at the rate of 0.24 inches per hour. On the first night, September 12-13, a 0.3 inch natural rain fell on the area at the same time as the irrigation was carried out on replication 1. Otherwise no rain fell during September 13-18 while these measurements were being made.

On September 14 aeration measurements, using the micro-electrode technique, were made on replication 1, where irrigation had been stopped about 25 hours before. The readings were taken fairly centrally on the plots and adjacent to the row of water table pipes and other equipment which had been set up on each plot by other workers present and interested in measuring the changes occurring in soil moisture conditions during the course of drainage. On the tiled plots the readings were taken about 3 feet on either side of the middle tile line. Soil samples for moisture determinations were taken for each ODR measurement made.

On September 17 and 18 a special study was carried out on plot 1 C (replication 1, treatment C) to see how the ODR and soil moisture content values were affected by the distance to the middle tile line. Measurements were made as in previous investigations at 0-2, 5-10 and 15-20 feet from either side of the tile.

3. Results and Discussion

The results of the ODR and moisture studies made on the drainage plots at the Ohio North-Central Substation are presented in Tables H and I in the Appendix. Table H contains the ODR values and Table I the corresponding moisture contents of the soil arranged according to the drainage treatment used and the time period elapsed since irrigation was stopped. Average values for each treatment and time period have also been calculated and presented in these tables as well as in Figure 36, which illustrates how the average ODR and moisture content values change for each treatment from 0 to 120 hours after irrigation.

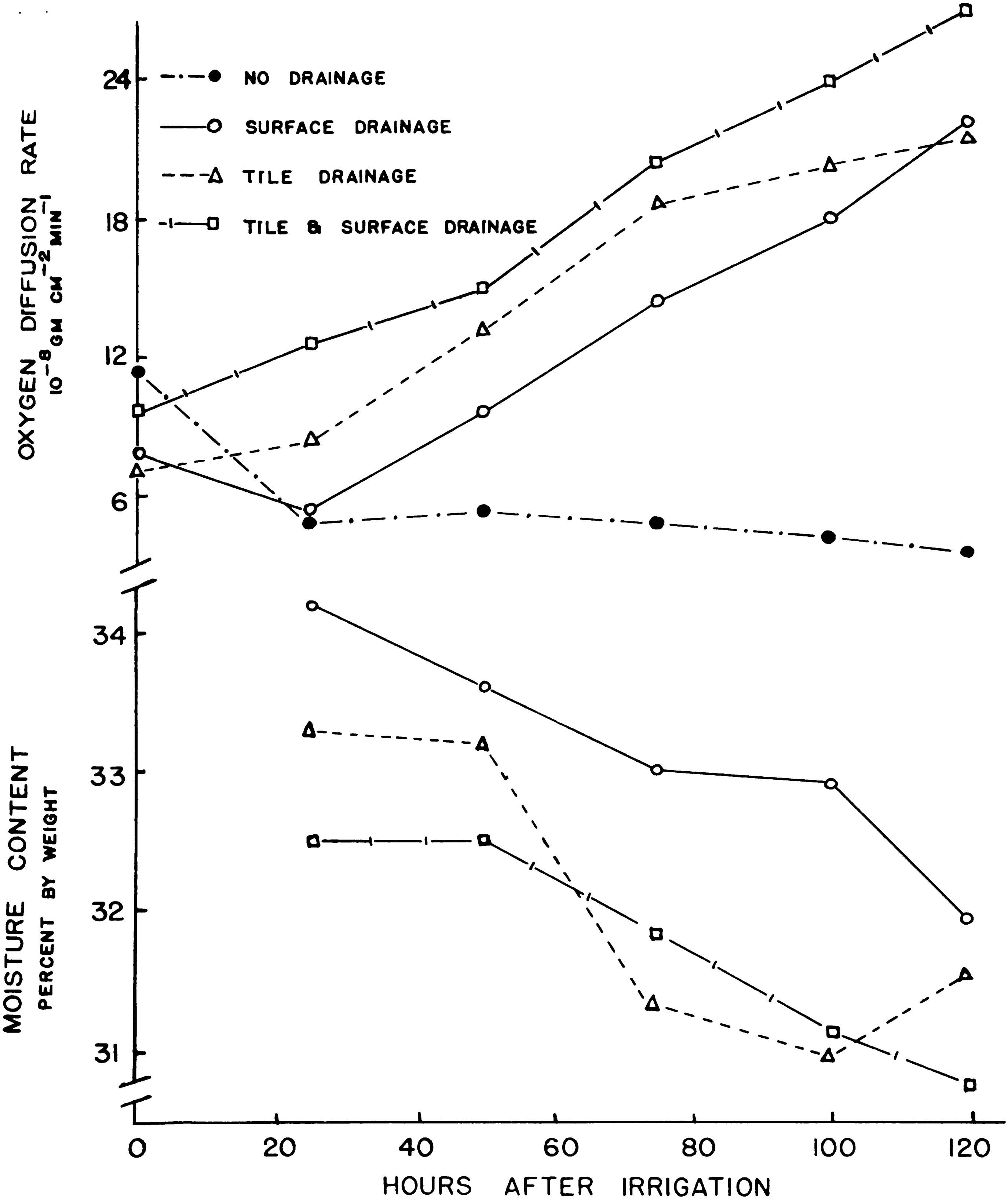


Figure 36. Changes in ODR and soil moisture content values with time after 4 inch irrigation application for different drainage treatments at the North-Central Substation, Ohio.

On the A plots, where no drainage treatment was applied, about 2 inches of surface water remained standing after the irrigation was stopped and showed very little if any tendency to seep away. In fact, on plot 1A which was the first of the no drainage plots to be irrigated, almost as much water remained on the surface at the end of six days after irrigation as was there on the same day that the irrigation was stopped. Exactly how deep into the soil the irrigation water had penetrated in these plots and at what depth the downward movement had been checked was difficult to determine, since the surface was covered with a deep layer of water, making investigations of the moisture status of the underlying soil very difficult indeed. The ODR values obtained on these plots showed a small but steady decrease with time indicating that the aeration conditions under the stagnant water were gradually becoming worse rather than improving (Figure 36). The Tall Fescue grass which covered the whole experimental area also showed the poorest stand on the A plots, due to the poor drainage conditions which prevailed there.

As regards the other three treatments where surface, tile or combined surface and tile drainage were used, all the surface water had run off within five or six hours from the time the irrigation was turned off. It was rather difficult to determine which of these treatments was the most effective in removing the surface water. However, even if such a difference could have been established, it would have been too small to have been of any great importance under the existing conditions.

In Figure 36 the difference between the ODR time curves for the undrained (A) treatment on the one hand and for the drained treatments on the other is brought out very clearly. The curves for the drained plots show a very steady increase with time, and after about 100 hours from irrigation, the ODR values have here more than doubled, where in the case of the undrained treatment the ODR value has instead decreased by about 20%. It is also rather interesting to note from Figure 36 that both the ODR-time curves and the moisture-time curves for drained treatments are all very closely linear in nature and furthermore have essentially the same slope. This would seem to indicate that over the time period here studied, the recovery of the oxygen diffusion rate in the soil and the removal of soil moisture in it are occurring as rapidly irrespective of whether surface, tile or combined surface and tile drainage is used. The only real difference between these drainage treatments seems to be the starting point.

From the moisture-time curves shown in the lower half of Figure 36 it can be seen that after 25 hours from irrigation, the surface drainage (B) has the highest moisture content at 34.2% followed by tile drainage (C) at 33.3% and then the combined surface and tile drainage (C) at 32.5 %, and that as far as treatments B and D are concerned the initial difference of 2% between their moisture contents is essentially maintained over the 100 hour period studied. Moisture curve C is a little irregular in that the values suddenly decrease after 50 hours and become lower than those for the D treatment until at 120 hours after irrigation, they increase again to the midway value between the B and D moisture curves.

A linear correlation analysis of the ODR-time relationship for each of the drainage treatments was made to see whether this would perhaps better establish any differences that may exist between the treatments. The results of the analysis are shown below, where Y represents the dependent ODR variable measured in 10^{-8} gm O_2 cm^{-2} min^{-1} and X the independent time variable measured in hours.

Treatment A	Regression equation:	$Y = 5.6 - 0.014X$
	Correlation coeff.	$r = 0.223$ N.S.
	Standard error of estimate	$s_{yx} = 1.6$
Treatment B	Regression equation:	$Y = 1.8 + 0.160X$
	Correlation coeff.	$r = 0.904^{**}$
	Standard error of estimate	$s_{yx} = 1.6$
Treatment C	Regression equation	$Y = 4.4 + 0.165X$
	Correlation coeff.	$r = 0.842^{**}$
	Standard error of estimate	$s_{yx} = 3.1$
Treatment D	Regression equation	$Y = 8.6 + 0.148X$
	Correlation coeff.	$r = 0.895^{**}$
	Standard error of estimate	$s_{yx} = 2.2$

** Significance at 1% level

N.S. Non-significance at 5% level

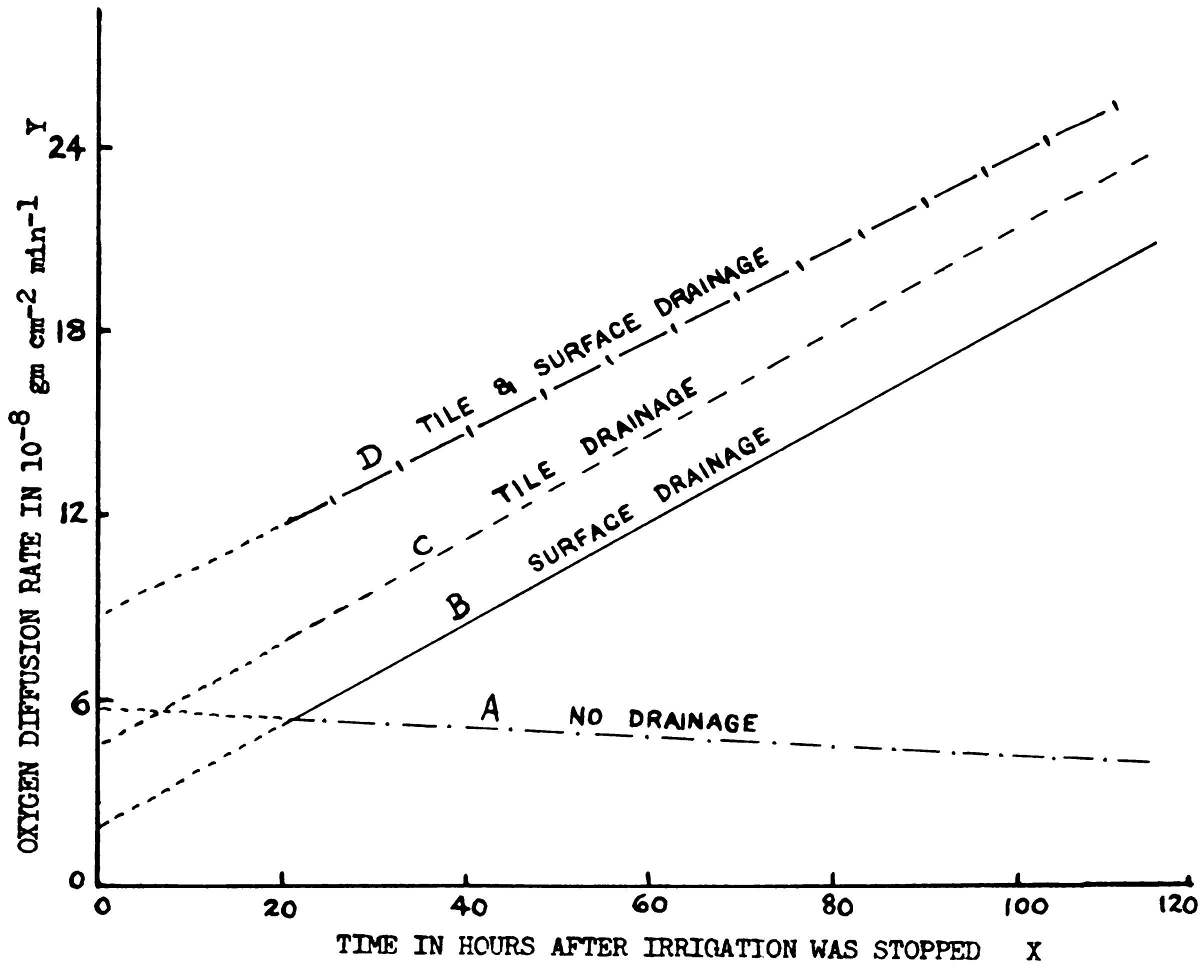


Figure 37. Regression lines showing how the ODR of the surface soil changed with time after 4 inches of irrigation water was applied to it under various drainage conditions at the North Central Substation of Ohio.

The regression lines for all treatments are shown graphically in Figure 37. From this it will be clearly seen that the curves for the B, C and D treatments are almost parallel, having positive gradients of 0.160, 0.165 and 0.184 respectively. Although the regression equations for treatments B, C and D are highly significant, that for treatment A is non-significant even at the 5% level and has a negative slope.

On September 17 and 18 a special set of ODR readings and soil moisture determinations were made on plot 1C (replication 1, tile drainage only) where respectively 100 and 120 hours had elapsed since irrigation. Six sets of measurements were made perpendicularly to the central tile line at distances of 0-2, 5-10, and 15-20 feet on either side of the tile line. The results are presented in Table J and graphically illustrated in Figure 38. It is rather interesting to note how flat the ODR curves are 5 to 20 feet on either side of the tile and how they suddenly increase in value by about 25% just above the tile line at the 0-2 feet location. This trend is also shown by the moisture curves, which pass through minimum values above the tile line. The drainage effect would therefore seem to be greatest immediately above the tile line and then fairly quickly decrease as the distance from the tile increases more than 2 feet or so. A comparison of the curves for the two days does show, however, that moisture is being removed fairly effectively all the way out to 20 feet from the tile. Thus a one percent drop in moisture content occurred at 20 feet from the tile from September 17 to 18.

In Figure 39 the average moisture content values for each treatment and time period taken from Table I have been plotted against

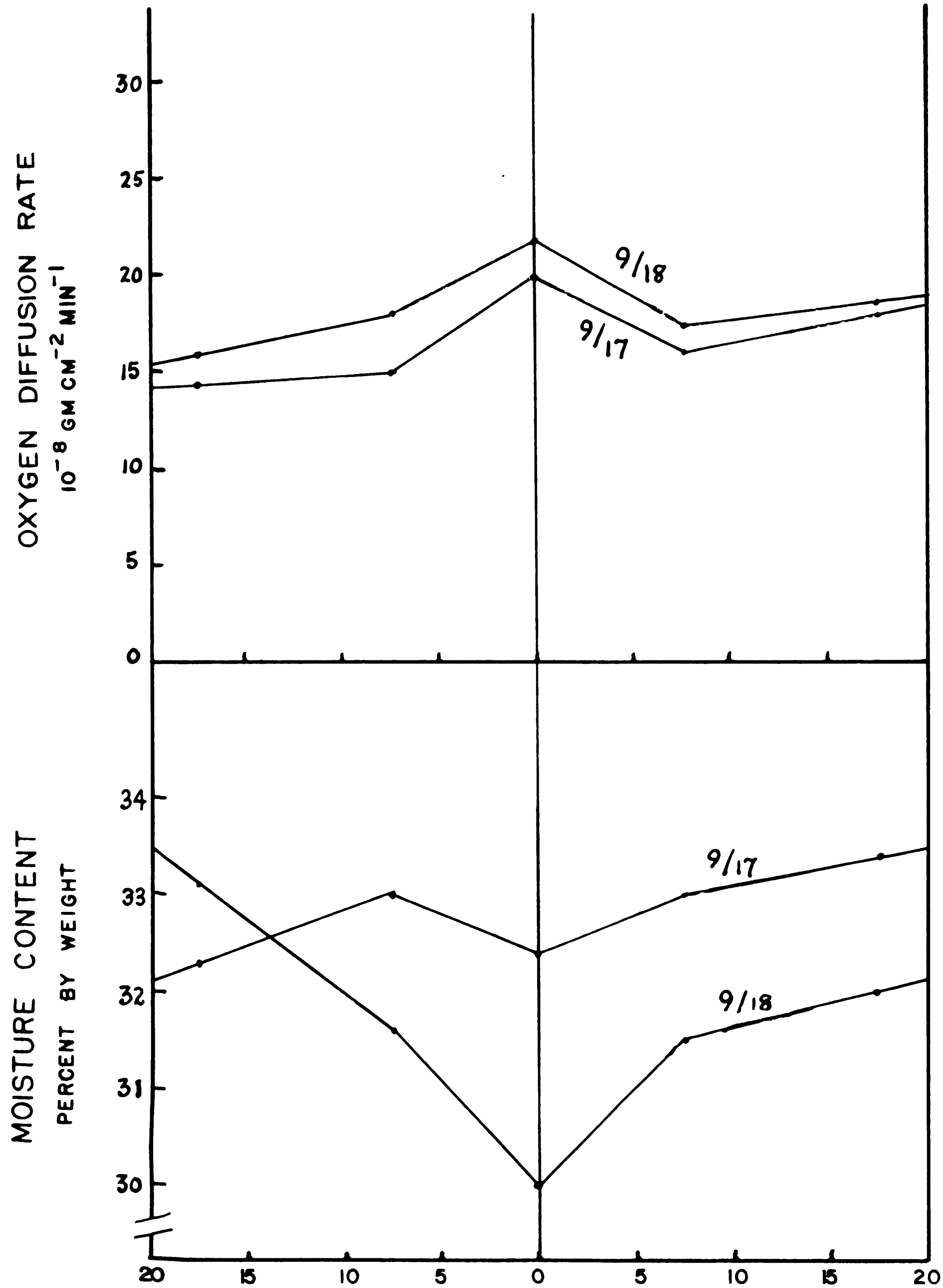


Figure 38. ODR values and soil moisture contents measured across a tile line at the North-Central Substation of Ohio.

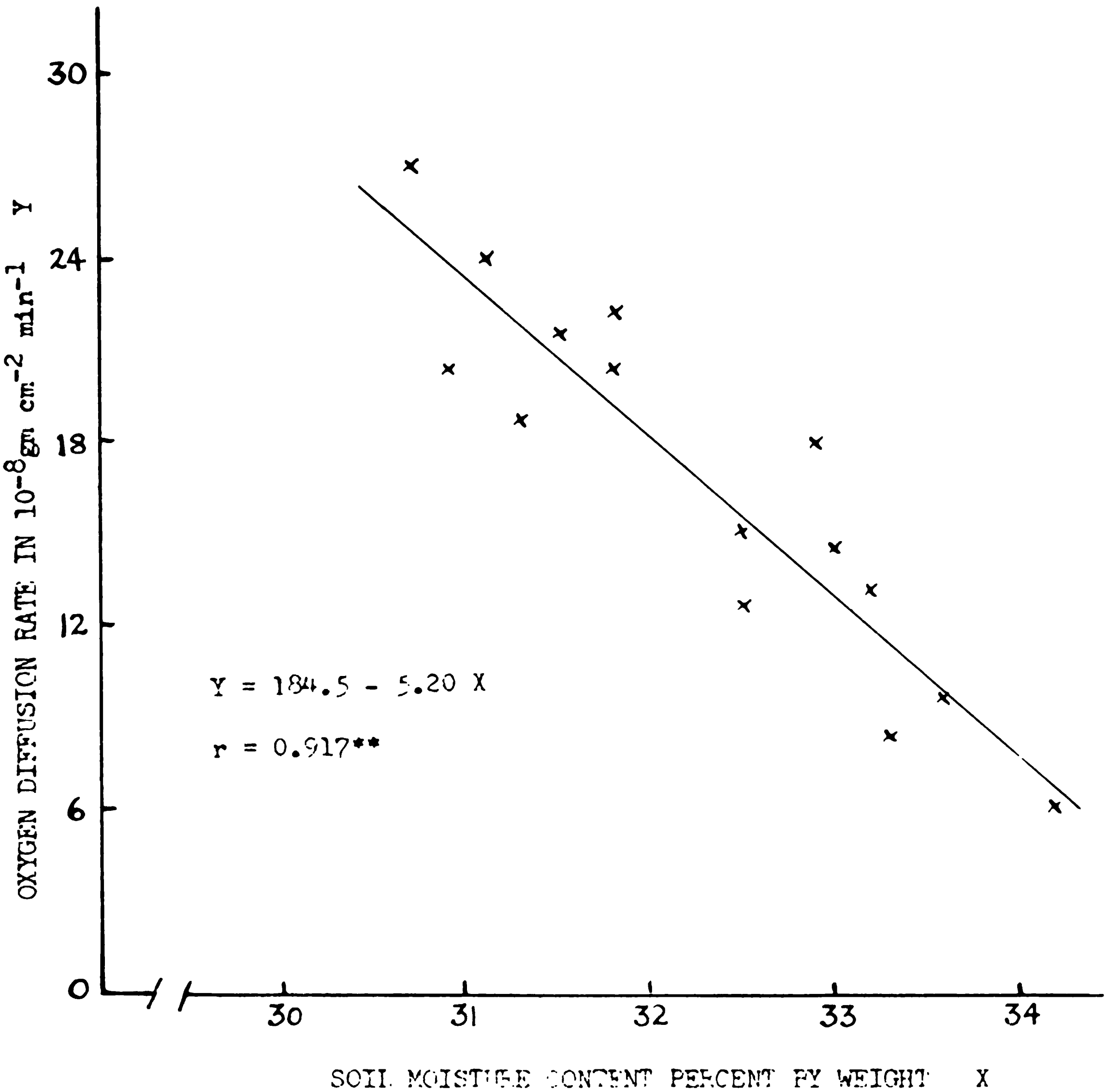


Figure 39. Plot of ODR versus moisture content for Toledo silty clay at the North-Central Substation of Ohio.

the corresponding average ODR values taken from Table H. On the basis of these values a simple linear correlation analysis has been made to find the regression equation for the line that best fits the values. The equation found was $Y = 184.5 - 5.20\ X$ and the correlation coefficient was 0.917, showing that the equation was very highly significant. Of course the values used for this analysis cover a rather limited range of both the ODR and soil moisture content regions, that is, from 5.9 to 26.6×10^{-8} gm O_2 cm^{-2} min^{-1} respectively, 30.7 to 34.2% by weight moisture, and therefore cannot be expected to adequately predict the regions outside this range. The high value of the regression coefficient (5.20) is rather interesting, however, in that it shows how very sensitive the microelectrode technique is to small changes in soil moisture content on the Toledo silty clay soil.

4. Summary

ODR and moisture content measurements were made in the surface soil at the Tile-Surface Drainage Experiment in Ohio to study how four different drainage treatments would affect these values after a 4 inch irrigation water application was made. The soil was Toledo silty clay, a poorly drained Humic-Gley.

On plots where no provisions had been made to facilitate drainage (treatment A), irrigation resulted in a ponded condition during the entire period studied, September 12-18, 1960. At the same time the ODR of the surface soil was kept very low because of this.

For all the drained plots, the surface water was removed within a few hours after irrigation was stopped. No differences were observed between drainage treatments as to their efficiency in removing surface water.

The ODR of the surface soil on the drained plots was low immediately after irrigation, but steadily increased for each day that passed after it. Simultaneously the moisture content decreased. The time rate of increase of ODR over the period studied was very steady (linear) and essentially the same for all three drainage treatments. Thus, the regression line for the ODR x time relationship of the surface soil on the combined surface and tiled plots (treatment D) had the same gradient as both the tile drained (treatment C) and surface drained (treatment B) plots. The intercepts were different, however, so that the intercept for treatment D > C > B. This seemed to indicate that there was a difference in the moisture and ODR conditions of the plots already before the irrigation was applied and that this difference was essentially maintained even after irrigation had been applied. Since studies had not been made of the soil conditions before irrigation was made, it was not possible to explain how or when these differences were established.

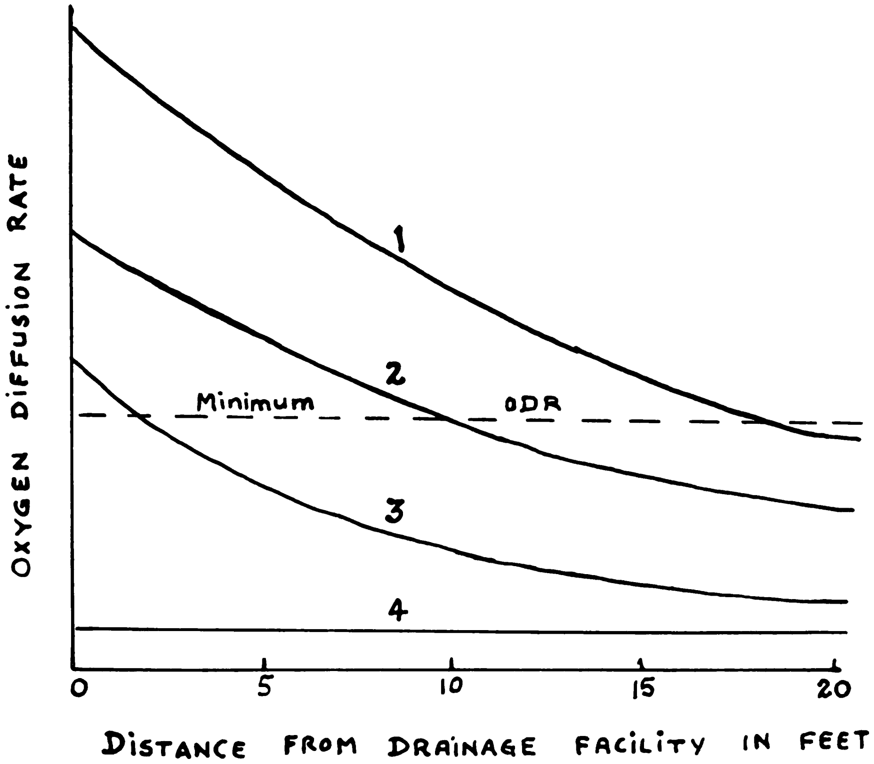
On two dates, September 17 and 18, ODR and moisture content determinations were made perpendicularly to a tile line on one of the tile-drained plots. The values were found to be very much affected by drainage immediately above the tile line, but at distances exceeding 5 feet from the tile remained fairly constant.

The regression equation for the relationship between ODR (Y value) and corresponding moisture content (X value) of the surface soil was $Y = 184.5 - 5.20\ X$, which was significant at the one percent level. The regression coefficient of 5.20 was the highest value received of any of the previous soils studied and indicated that for the Toledo silty clay soil, the ODR changed very rapidly with changes in moisture content.

G. Discussion

The field studies have shown that a great deal of information regarding the effects of various methods and intensities of drainage can be obtained by simply measuring the ODR of the surface soil with the platinum microelectrode technique. The ODR is an expression for the rate at which oxygen diffuses through the liquid phase of the soil, and in the surface horizon is the main factor that will limit the oxygen supply to the plant roots. Drainage will affect the ODR by reducing the thickness of the liquid phase (moisture film) around the electrode.

Field studies were carried out at five locations that had different soil and drainage conditions. At all locations the effects of tile drainage on the ODR of the surface soil were studied by making measurements with the platinum microelectrode at regular distances perpendicular to the tile. At one location (the Crawford Farm) the effect of bedding on the ODR was similarly studied by making measurements perpendicular to the bed-ridge. At another location (North-Central Substation of Ohio) ODR measurements were made to compare the effects of no drainage, surface drainage, tile drainage and combined surface and tile drainage on the same soil. A schematic diagram such as that shown below essentially summarizes the results of these studies.



This diagram illustrates the relation between the ODR of the surface soil and the perpendicular distance of the soil to the drainage facility (tile or bed ridge). The soil is assumed to be one that under natural conditions is poorly drained and has a fairly low hydraulic conductivity. The measurements are assumed to have all been made at the same time on plots where the soil has been treated with:

1. Combined bedding and tile drainage
2. Tile drainage
3. Bedding
4. No drainage

If it is assumed that the dotted line shown in the diagram marks the "minimum ODR" (see Erickson and Van Doren 1960), below which the plant roots will suffer from oxygen deficiency, it will be seen that this crosses the ODR curves at different distances from the drainage facility. Thus the combined bedded and tiled soil will have a sufficient oxygen supply for the roots 0 to 18 feet from the tile and bed ridge or in other words, over 90% of the soil will have adequate aeration. On the other hand, the tiled soil will only have adequate aeration from 0 to 10 feet from the tile (i.e. 50% of the soil), while the bedded land will have adequate aeration from only 0 to 2 feet from the bed ridge or for as little as 10% of all the soil present. The undrained soil is assumed in this case to have very poor drainage and aeration conditions and therefore to be quite unsuitable for crop production.

From a diagram such as that shown, it should be possible to determine the spacing of the drainage facility that is required to achieve adequate aeration in soil across the entire field. In the example given here the 40 feet spacing already used for the combined bedding and tile drainage is essentially adequate, while for the tile drainage alone closer spacing would be necessary or about 20 feet between the tiles. The bedded and undrained soil will both need to be tile drained, since bedding at 4 feet spacing which is shown to be necessary, will be impractical.

The field studies also included measurements of the ODR and moisture content of the surface soil taken over a period of time. These values were then found to fluctuate in opposite directions due to the combined effects of rainfall and drainage. Cyclic time curves were obtained for each, where the ODR time curve was displaced half a period in relation to the moisture curve. These results have been generalized and schematically illustrated in Figure 40. A medium textured soil with a fairly high hydraulic conductivity is assumed to be subject to both a well drained and a poorly drained condition. At the beginning of the period the soil is assumed to be saturated with water and on the 8th and 15th day rain is received. Figure 40 shows how the moisture content (upper half) and ODR (lower half) of the soil fluctuate with time over a 17 day period under both drainage conditions. The wilting point and the "minimum rate" of oxygen supply for the soil are indicated and the periods during which water or oxygen deficiency prevailed are shaded on the figure. This shows that under well drained conditions the soil was water deficient between the 6th and 8th day and the 13th and 15th day (total of 4 days) while for the poorly drained conditions the moisture content remained above the wilting point throughout the period, so that it was never water deficient.

When the ODR curves are studied it will be seen that the well drained soil was oxygen deficient between the start and the 2nd day. 8th to middle of 10th day and 15th to 17th day (total of 6.5 days) while the poorly drained soil lacked an adequate oxygen supply for the plants between the start and the middle of the 5th day, 8th to 13th and 15th to 17th day (a total of 12.5 days). During the 17 days studied, the period over which both the water and oxygen supply of the soil were adequate to the plants was 6.5 days for the well drained condition (17-4-6.5 = 6.5) and 4.5 days for the poorly drained condition (17-0-12.5 = 4.5). Thus the greater the gradient of the curves the

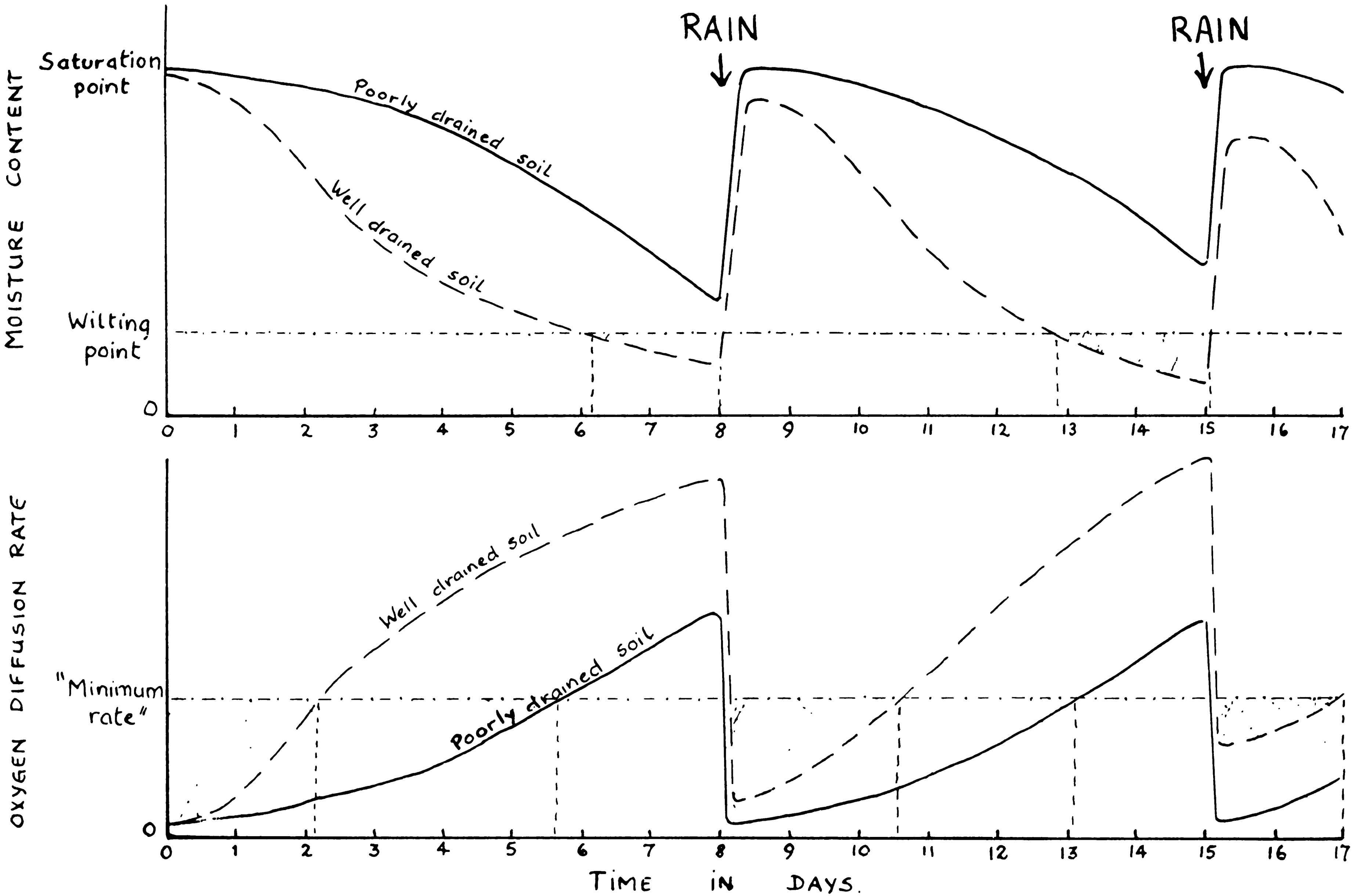


Figure 40. The variation in ODR and moisture content of a soil undergoing well drained and poorly drained conditions. (Hypothetical)

longer were the water deficient periods and the shorter the oxygen deficient periods and vice versa. Since plants are much more tolerant towards water deficiencies than oxygen deficiencies the optimum gradient of the curves should be based on the ODR-time relationship rather than the moisture-time curve. Furthermore, water should not be drained from the soil in amounts greater than necessary to rapidly reach adequate aeration conditions. After this condition is reached all further loss of water should, if possible, be prevented.

At each of the five locations studied highly significant linear relationships were found between the soil moisture content and corresponding ODR measured with the microelectrode. The regression lines are shown together for purposes of comparison in Figure 41. The lines for the Soil Science Farm (Brookston loam), Farm Crops Farm (Conover loam) and Ferden Farm (Sims clay loam) have almost identical gradients and differ only in the value of the intercept. The lines for the two clay soils, Crawford Farm (Pickford clay) and the Ohio Substation (Toledo silty clay) differ, however, in both gradient and intercept. The equations are:

1. $Y = 94.6 - 2.82\ X$ (Brookston loam)
2. $Y = 91.8 - 2.82\ X$ (Conover loam)
3. $Y = 109.6 - 2.94\ X$ (Sims clay loam)
4. $Y = 89.3 - 2.16\ X$ (Pickford clay)
5. $Y = 184.5 - 5.20\ X$ (Toledo silty clay)

Although all the above equations are highly significant, it would seem that ODR (the rate factor) might better be related to the

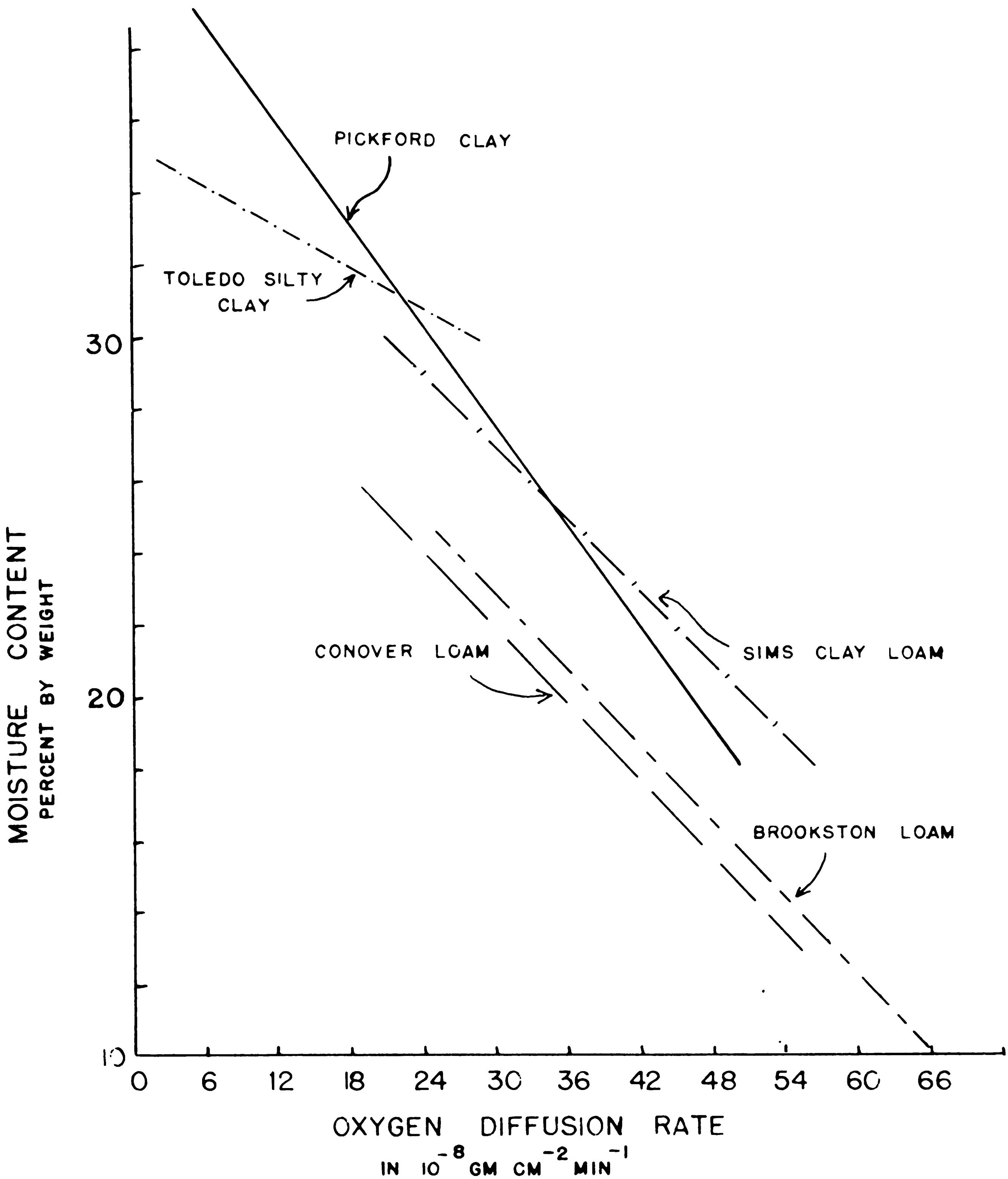


Figure 41. ODR-moisture curves for the different soils studied.

air content of the soil (the capacity factor). Since core samples were taken of the soil at all locations except at the Ohio substation and moisture retention measurements were made, the moisture contents measured can be converted to the equivalent air content of the soil, by using the following equation:

$$n_a = (n_t - G_a X)$$

where n_t is the total porosity of the soil expressed on a volume basis and n_a is the air content expressed on a volume basis,

G_a is the bulk density of the soil in gm cm^{-3}

X is the moisture content in percent by weight.

From this equation $X = \frac{(n_t - n_a)}{G_a}$ which can be substituted into the regression equations to give a new series of equations relating ODR with equivalent air contents. Thus:

1. $Y = 19.8 + 1.80\ n_a$ (Brookston loam)
2. $Y = 1.8 + 2.10\ n_a$ (Conover loam)
3. $Y = -0.6 + 2.34\ n_a$ (Sims clay loam)
4. $Y = -6.6 + 1.86\ n_a$ (Pickford clay)
5. Core samples not taken

When these equations are compared with the original ones, it will be seen that rather than being drawn closer together, the transformation has caused the lines to instead separate further apart. Thus the difference in intercept between the outer lines is now 26×10^{-8} gm cm^{-2} min^{-1} as compared with a previous 20×10^{-8} gm cm^{-2} min^{-1}. On the other hand the variation in their gradients (regression coefficients) has somewhat decreased from a previous 0.78 to a present 0.54. It would seem, however, as if some other parameter such as the thickness of the moisture film around the electrode, which occurs directly in the Rate Equation (see equation 13) would be better to relate to the ODR than either the moisture or air content here used. This will be further discussed in the next chapter concerning the laboratory studies.

A rather interesting point brought out by the regression equations is the very marked relationship which exists between the ODR and soil moisture content. Thus for a 5-10% change in moisture content there is a corresponding 15-25% change in ODR. In other words the ODR measured with the platinum microelectrode changes 2-3 times as fast as the corresponding moisture content. This also explains why the platinum microelectrode has been so successful in bringing out even the smallest effects of drainage in this study and why the plant roots are so dependent on drainage for an adequate supply of oxygen.

CHAPTER IV

LABORATORY STUDIES

A. Introduction

1. The Diffusion of Oxygen to the Platinum Microelectrode

The platinum microelectrode causes oxygen to be electrolytically reduced at its surface so that an oxygen concentration gradient is set up between it and the soil medium. As time progresses the boundary for this concentration gradient moves outwards from the electrode, extending further and further into the heterogeneous medium surrounding it. As it does so, the magnitude of the gradient will change, partly because of the increase in distance to the electrode and partly because of the changes in oxygen ocncentration which will occur as the boundary encounters different phases of the soil medium (solid particles and gas filled pores, etc.). These changes will also be reflected in the shape of the current-time curve measured with the electrode. Usually after 3-5 minutes time a steady state condition is reached, where the oxygen concentration gradient has moved out so far that the diffusion of oxygen from the medium surrounding its boundary will be just as rapid as the diffusion of oxygen within this boundary to the electrode surface. The current received under these conditions is the steady state oxygen diffusion current (ODC) and its magnitude will be determined by the nature of both the electrode and the soil medium surrounding it.

From the Rate Equation earlier derived (13), it was found that the rate of flow of oxygen F to the plant root from the soil medium surrounding it was expressed as:

$$F = DA \; \frac{C_p - C_r}{L}$$

where D is the diffusion coefficient of oxygen through the moisture film, A is area of the root, $(C_p - C_r)$ is the difference in oxygen concentration between the moisture film interface at the air-pore and root surface respectively and L is the thickness of the moisture film. For the platinum microelectrode, ODR = F/A and C_r can be assumed to be zero, so that:

$$ODR = D \; \frac{C_p}{L} \qquad (18)$$

Of the variables involved in this equation only L, the thickness of the moisture film surrounding the electrode, is uniquely related to drainage. C_p and D are only indirectly dependent on drainage, since they are also affected by other factors. The best way of expressing the effect of drainage on soil aeration (oxygen diffusion through the liquid phase) would therefore seem to be in terms of moisture film thickness L. From the equation above, L can be found from the ODR measured, so that

$$L = D \; C_p \; (ODR)^{-1} \qquad (19)$$

Wiegand and Lemon 1958 report favorable results from the use of this term for expressing the aeration properties of a soil. Because of the heterogeneous nature of the soil and the moisture film that will surround the electrode there, they have defined L as the "apparent diffusion path length" rather than the film thickness. By this is meant the distance over which the concentration gradient is active when the diffusion process has reached steady state conditions.

2. The Apparent Diffusion Path Length

Wiegand and Lemon 1958 determine the apparent diffusion path length by assuming radial diffusion of oxygen to the platinum micro-electrode and make use of Fick's second law of diffusion to derive a suitable mathematical expression.

Ficks second law of diffusion in one dimension in rectangular coordinates is:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}$$

and in cylindrical coordinates becomes:

$$\frac{\partial c}{\partial t} = D\left(\frac{\partial^2 c}{\partial r^2} + \frac{\partial c}{r \partial r} + \frac{\partial^2 c}{r^2 \partial \phi^2} + \frac{\partial^2 c}{\partial z^2}\right) \tag{20}$$

By assuming symmetry about the cylindrical axis and that no longitudinal concentration gradients exist (20) becomes:

$$\frac{\partial c}{\partial t} = D\left(\frac{\partial^2 c}{\partial r^2} + \frac{1}{r}\frac{\partial c}{\partial r}\right) \tag{21}$$

But for steady state conditions $\frac{\partial c}{\partial t} = 0$ and

$$D \frac{\partial^2 c}{\partial r^2} + \frac{\partial c}{r \partial r} = 0 \qquad (22)$$

the general solution of which is:

$$C = k_1 \ln r + k_2 \qquad (23)$$

If the radius of the electrode is R cm and the radius of the electrode plus the diffusion boundary is r_e cm, the apparent diffusion path length is $(r_e - R)$ cm

Let C_e = oxygen concentration in g cm^{-3} at some point r between R and r_e, that is within the boundary.

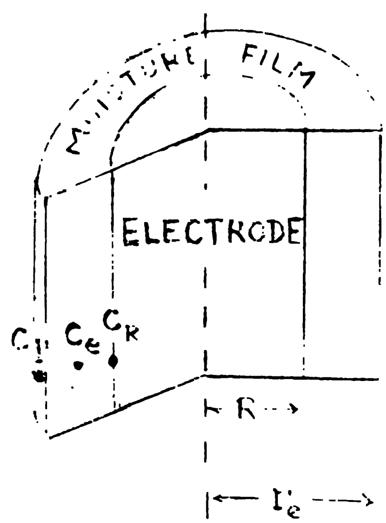
C_p = oxygen concentration in g cm^{-3} in the air-liquid interfase at r_e.

C_R = oxygen concentration in g cm^{-3} at the platinum surface R.

The boundary conditions are:

$C_e = C_R$ when $r = R$

$C_e = C_p$ when $r = r_e$



and from (23) these will give three equations:

$$C_e = k_1 \ln r + k_2 \qquad (24)$$

$$C_R = k_1 \ln R + k_2 \qquad (25)$$

$$C_p = k_1 \ln r + k_2 \qquad (26)$$

Combining (25) and (26)

$$k_1 = \frac{C_R - C_p}{\ln R - \ln r_e} \qquad (27)$$

which when substituted into (24) gives

$$C_e = \frac{(C_R - C_p)\ln r}{\ln R - \ln r_e} + k_2 \tag{28}$$

Differentiation of (28) with respect to r gives

$$\frac{d\,C_e}{dr} = \frac{(C_R - C_p)}{\ln R - \ln r_e} \cdot \frac{1}{r} \tag{29}$$

But Fick's first law states that

$$F = A \cdot D_e \frac{dC_e}{dr} \tag{30}$$

where F = flux of oxygen to the surface of electrode in gm cm^{-2} sec^{-1}

A = area of electrode in cm^2

D_e = diffusion coefficient of oxygen in the soil solution in cm^2 sec^{-1}

Substituting equation (29) into (30)

$$F = \frac{A\, D_e\, (C_R - C_p)}{r\,(\ln R - \ln r_e)} \tag{31}$$

and

$$r_e = R\, e^{\left(- \frac{A\, D_e (C_R - C_p)}{r\, F} \right)} \tag{32}$$

But for the measurements with the electrode

$A = 2\pi R\, l$

where l = 0.4 cm and is the length of the electrode

and R = 0.032 cm and is its radius

Also $C_R = 0$

and $r = R$ since the flux is measured at the electrode surface.

The concentration of oxygen at the air-liquid interface C_p can be found by measuring the partial pressure of oxygen in the air phase of the soil and then assuming the interface to be in equilibrium with this. If the interface is in equilibrium with air containing 20.9% oxygen and having a barometric pressure of 760 mm, then at 26°C

$$C_p = 8.3 \times 10^{-6} \text{ gm cm}^{-3}$$

The diffusion coefficient of oxygen in the soil solution D_e has been determined by Lemon at 26°C to be

$$D_e = 2.2 \times 10^{-5} \text{ cm}^2 \text{ sec}^{-1}$$

Equation (32) will then become

$$r_e = R\, e^{\frac{2\pi l D_e C_p}{F}}$$

$$= 0.032\, e^{\frac{(6.28)(0.4)(2.2 \times 10^{-5})(8.3 \times 10^{-6})60}{(0.08)(\text{ODR})}}$$

where F has been substituted for the ODR measured with the electrode.

That is $$F = \frac{A \times \text{ODR}}{60 \text{ sec.}} = \frac{0.08 \times \text{ODR}}{60}$$

and $$r_e = 0.032\, e^{\frac{34.4 \times 10^{-8}}{\text{ODR}}} \qquad (33)$$

When various values of the ODR are substituted into equation (33) the results shown in Table 2 are obtained.

TABLE 2

CALCULATIONS OF APPARENT DIFFUSION PATH LENGTH USING EQUATION (33)

ODR in 10^{-8}g cm^{-2} min^{-1}	Radius of diffusion boundary from axis of electrode r_e in cm	Apparent diffusion path-length $(r_e - R)$ cm
1	2.8×10^{13}	2.8×10^{13}
10	1.00	0.97
20	0.18	0.15
30	0.10	0.07
40	0.075	0.04
50	0.064	0.03

From this table it will be noticed that for the assumptions made, the apparent diffusion path length is less than 1 cm for ODR values exceeding 10×10^{-8} g cm^{-2} min^{-1} and that it then grows very rapidly for ODR values less than this value to meters and even kilometers in length (theoretically).

As pointed out by Wiegand and Lemon the apparent diffusion path length really represents a mean effective length, the actual pathway of which is tortuous in nature and depends on the geometry of the gas, liquid and solid phases of the soil surrounding the electrode.

3. The Diffusion Coefficient

The diffusion coefficient D_e employed in equation (37) has been obtained by Lemon by correcting the diffusion coefficient D measured in water for factors such as the tortuosity characteristics of the medium, the volume fraction of water it contains, etc. which all affect diffusion through the porous soil medium. By measuring D_e experimentally under well defined conditions, but in the same type of environment as encountered in the soil around the electrode, a value of it can be obtained, which will automatically be corrected for these values. Lemon has used a cylindrical vessel similar to that used by Laitinen and Kolthoff 1952, where a purely linear diffusion process is set up. Mathematically, this linear process is also described by Fick's second law of diffusion, from which an expression can be obtained for the concentration gradient $\frac{\partial c}{\partial x}$ occurring at the surface of the electrode ($x = 0$) at any instant t after the diffusion process is started. The boundary conditions which apply are:

$C_o = C$ when $t = 0$

$C_o = 0$ when $t \quad 0$

Where C_o is the concentration of oxygen in moles per cm^3 at the electrode surface and C the concentration in the body of the medium.

Under these conditions and at $x = 0$ (i.e. the gradient is measured at the electrode surface), Fick's equation yields:

$$\left(\frac{\partial C}{\partial x}\right)_{x=0} = \frac{C}{\sqrt{\pi D_e t}} \tag{34}$$

When this is combined with the equation for the electric current i produced by the electrode

$$i = nFAD_e \left(\frac{\partial C}{\partial x}\right)_{x=0} \tag{35}$$

the following expression is obtained:

$$i = nFCA\sqrt{\frac{D_e}{\pi t}} \tag{36}$$

which can also be written:

$$i = nFCA\sqrt{\frac{D}{\pi}}\left(\sqrt{\frac{1}{t}}\right) \tag{37}$$

and shows that since $(nFCA\sqrt{\frac{D}{\pi}})$ is constant for each medium used (assuming D does not change with concentration), the current i is linearly dependent on $\sqrt{\frac{1}{t}}$. Thus by plotting i against $\sqrt{\frac{1}{t}}$ the gradient obtained will be equal to $(nFCA\sqrt{\frac{D}{\pi}})$. In other words

$$\begin{aligned} D_e &= \frac{\pi}{(nFCA)^2}\left(i\sqrt{t}\right)^2 \\ &= \frac{\pi}{(nFCA)^2}\,(\text{gradient})^2 \end{aligned} \tag{38}$$

Thus by using a long cylindrical diffusion vessel, the bottom of which contains a flat platinum electrode to act as an oxygen sink, the linear diffusion of oxygen through various soil medias placed in this vessel can be studied and values of D_e be calculated from equation (38) and the current-time curves recorded.

4. Purpose of Laboratory Studies

The purpose of the present laboratory study was to construct an apparatus as described above and with it study how the moisture content of a porous medium affects the current-time curve and therefore the diffusivity D_e of oxygen through the medium.

B. Apparatus and Methods

The apparatus which was developed for the oxygen diffusion studies is shown in Figure 42. Its construction was based on the system used by Haines 1930 for studying the relation between moisture tension and corresponding moisture content of porous media. It consisted of a 5 ml micro-burette G (65 cm in length) connected to an adjacent diffusion cell A-B. The diffusion cell was made up of two parts, an upper 100 mm long plastic tube A with inner diameter 12.7 mm and a lower 60 mm long plastic tube B with inner diameter 16 mm. Both tubes had the same outer diameter of 19 mm and tube A, which had the thicker wall was machined so that it fitted tightly into the lower tube B, which contained a flat platinum disc electrode as well as a silver-silver chloride reference electrode. The platinum disc electrode was 12.7 mm

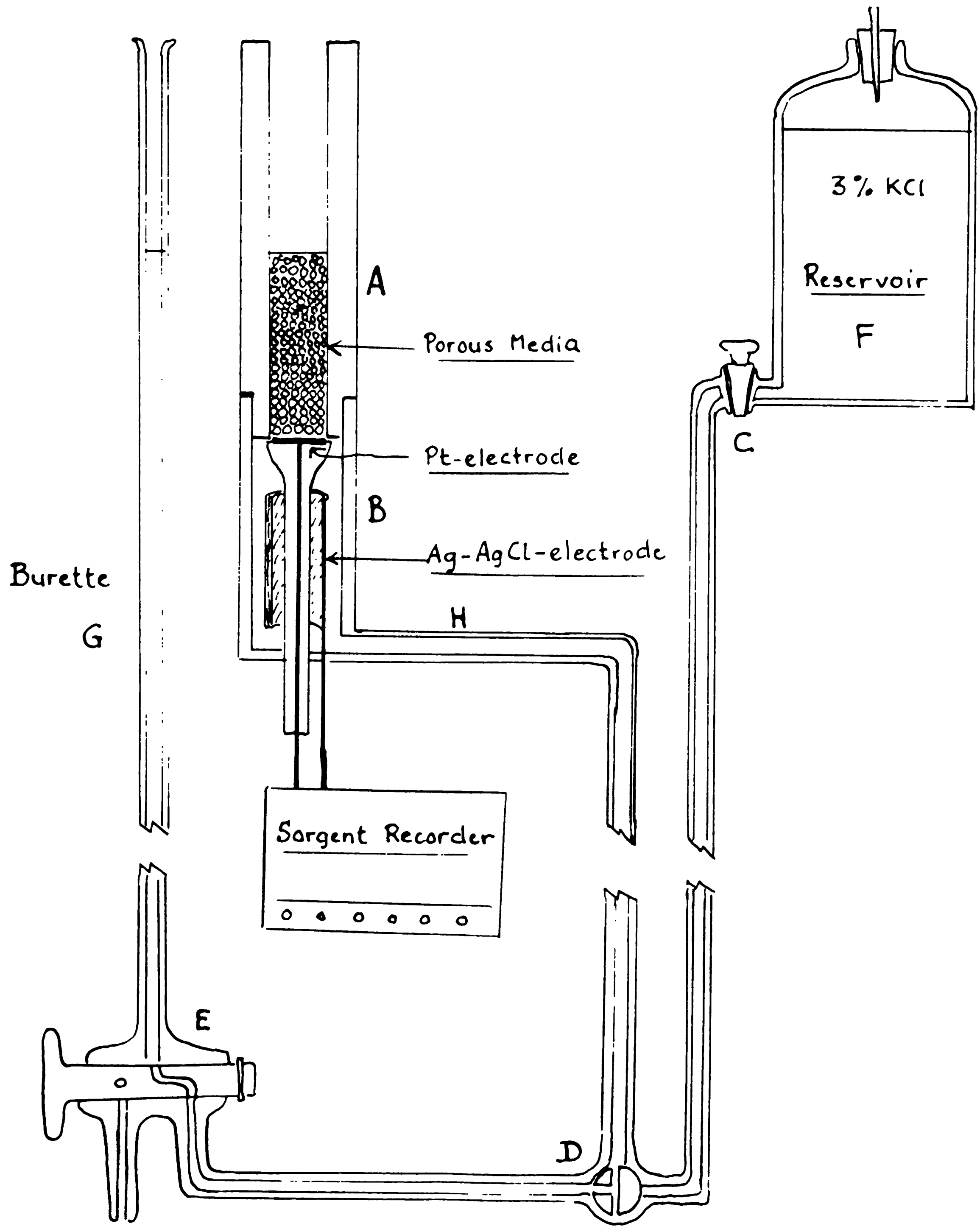


Figure 42. Apparatus used for oxygen diffusion studies in porous media.

in diameter and was mounted in a plastic holder about 14 mm in diameter. Electric connections from both electrodes were brought out at the bottom of the lower tube, where there was also a small tube H leading to the burette. When the machined end of tube A was pressed into tube B, it just touched against the rim of the platinum disc, so that the bottom end was completely covered by the flat platinum disc. Between the rim and the tube edge a few thin rings of filter paper were placed to give a better liquid contact between the upper and lower tubes when the whole apparatus was filled with 0.5 N KCl solution. The KCl solution was introduced at the bottom of the apparatus from a reservoir F, so that air could be more effectively excluded. Several taps C, D and E were used so that the various parts of the apparatus could be connected or disconnected as desired.

When measurements were made, the diffusion medium was placed in tube A above the Pt disc. The amount of KCl solution desired in A was adjusted by either adding solution from the reservoir F or removing it from the burette G, taps C, D and E being correspondingly adjusted. The moisture content in the diffusion cylinder A could thus be exactly regulated. Moisture tensions up to about 60 cm of water could also be applied to the medium in A by disconnecting reservoir F with tap C and using burette G as a manometer. This was done by first emptying G to the desired height and then connecting it to A by means of tap E. The increment of water drawn out of A could also be read from the change in height of the water level in G.

When the moisture of the medium had been adjusted to the desired level a potential of 0.65 volts was applied between the platinum disc and Ag-AgCl electrode and the current produced was recorded on a Sargent Recorder. This automatically gave a current-time curve corresponding to the oxygen diffusion process set up in the medium contained in A.

All the measurements were made in a constant temperature room maintained at 25.0 ± 0.5°C.

C. Results and Discussion

1. A Study of the ODR Through Moisture Films of Varying Thickness

Current-time curves were recorded when the diffusion chamber A was filled with various thicknesses of air saturated 0.5N KCl solution. The thickness varied from 50 mm to fractions of a millimeter.

The apparatus used here made it possible to arrange an almost flat meniscus (air-liquid interface) in the diffusion chamber. This was due to the poor wetting properties of the plastic tube comprising the chamber and to the introduction of KCl solution from below which helped to press up the central part of the meniscus. The thickness of the film could only be measured to the nearest 0.2 mm. For this measurement use was made of both the adjacent micro-burette, where the level in equilibrium with that in the diffusion chamber could be read fairly accurately, and partly by use of a vernier caliper applied on the outside of the tube.

Fresh KCl solution was used for each thickness measured and 0.65 volt was the potential applied. In order to permit a correction for the residual current produced by the electrode, a special current-time curve was run when the diffusion chamber was filled with de-aerated KCl solution (N_2 saturated). This is shown in Figure 43, from which it will be seen that the residual current very rapidly decreased to a value just above one microampere after one minute and a value less than one microampere (more precisely 0.7 microamps) after five minutes.

The current-time curves recorded were to a certain extent dependent on the history of the platinum electrode. Higher ODC values were always obtained for the first recordings made, due to the oxygen adsorbed on the platinum surface. After the electrode had been in use for about 30 minutes, however, and as long as it was not left standing without use for more than 30 minutes, the current-time curves recorded for the same film thickness were found to be quite reproducible. Fresh KCl had to be used for each film measured, otherwise residual effects from the diffusion zone set up in the previous measurement would be noticeable and cause lower ODC values.

The current-time curves recorded for various film thicknesses are shown in Figure 43 and will be seen to have very much the same shape and to reach constant values after about 2 minutes time. From Fick's second law of diffusion it is possible to calculate how far out the diffusion boundary will move from the electrode under linear diffusion conditions, see Kolhoff and Lingane 1952. Thus assuming a diffusion coefficient of 2×10^{-5} cm^2 sec^{-1} for oxygen in 0.5 N KCl solution, Figure 44 was constructed to show how the distance of the boundary from the electrode surface increases with time. This analysis shows that within the first 10 seconds, the boundary has only moved 0.6 mm from the electrode.

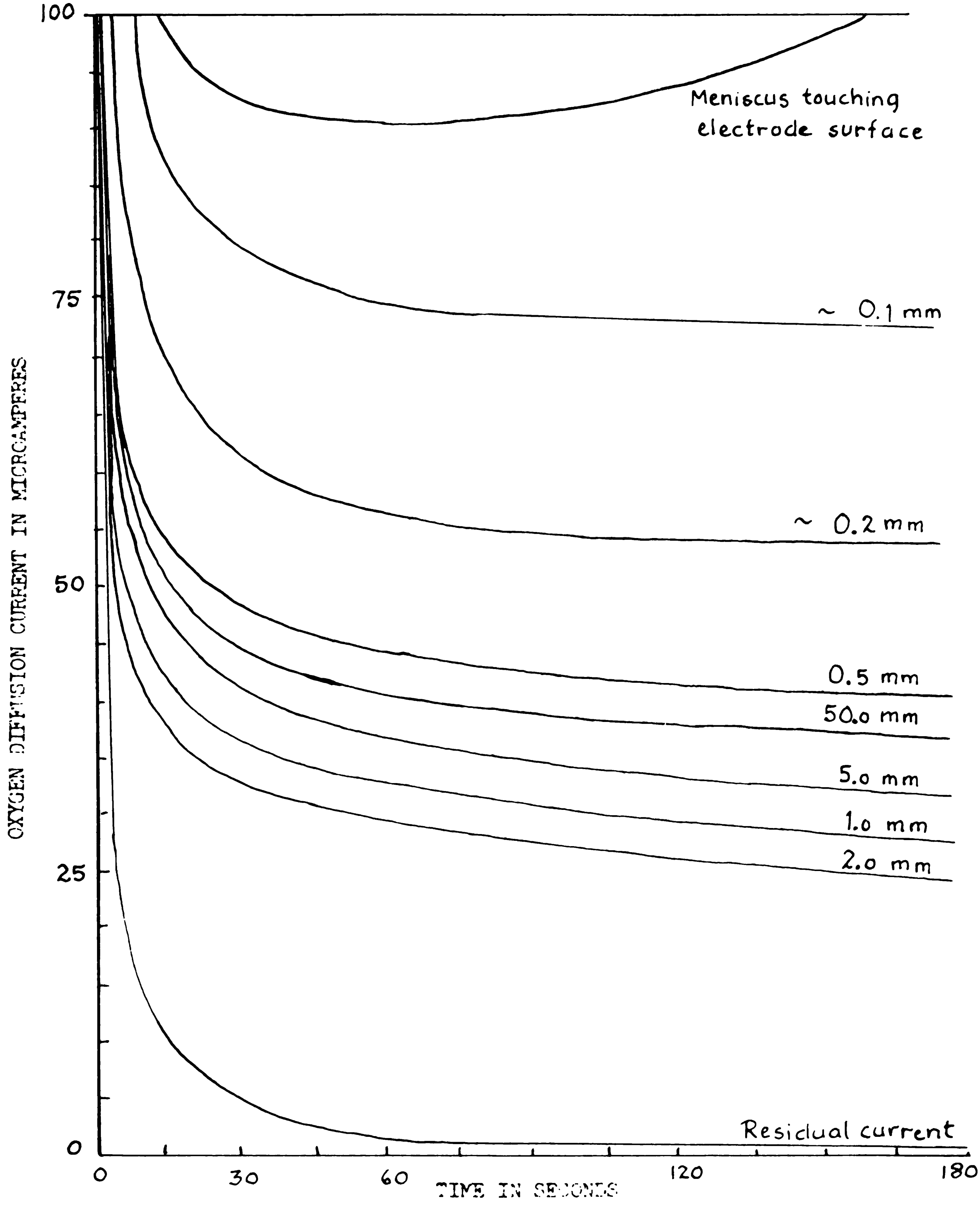


Figure 43. Current-time curves for various thicknesses of 0.5 N KCl solution.

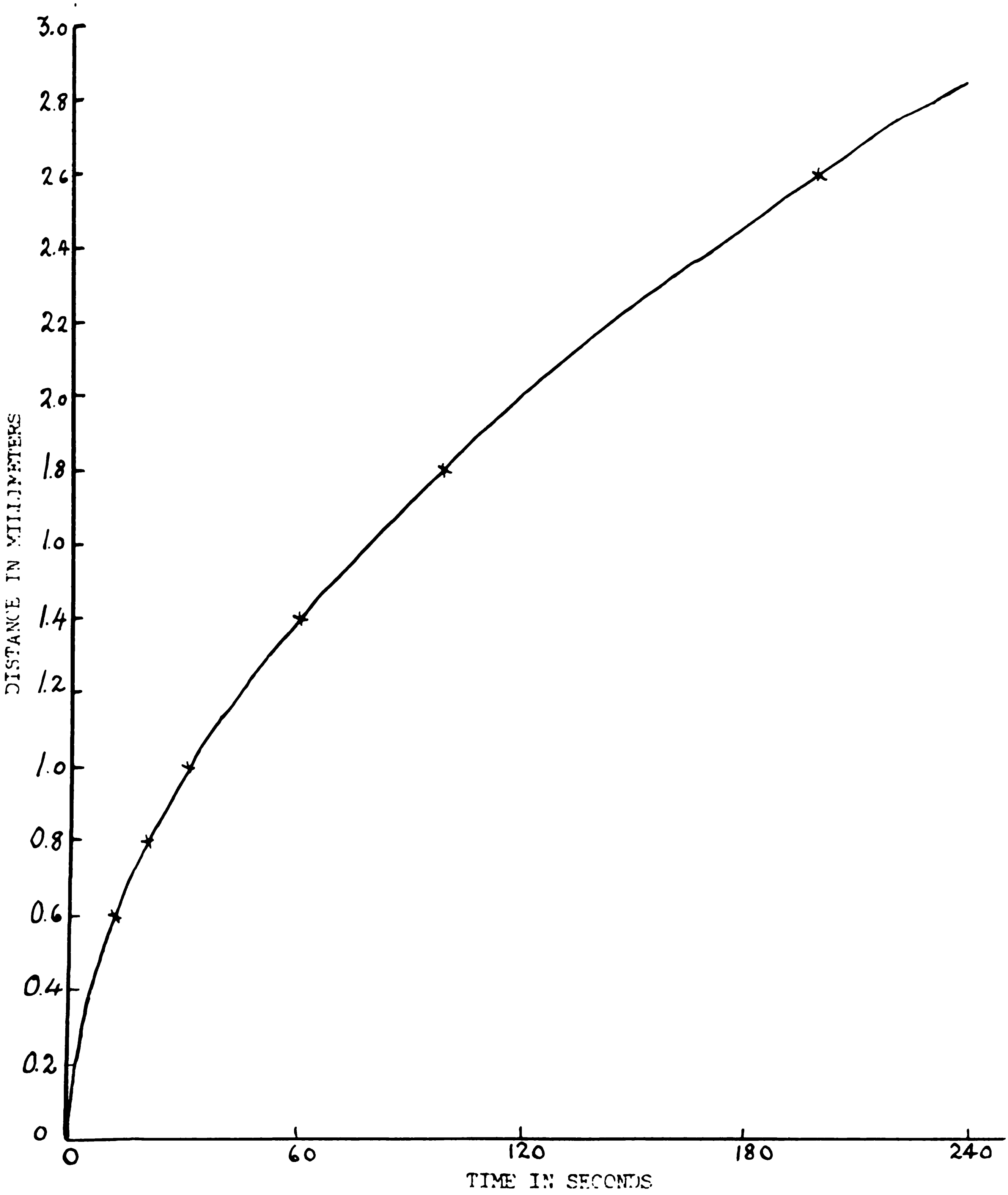


Figure 44. Distance of diffusion boundary from electrode surface at various times after start of linear diffusion process. D assumed to be 2 x 10^{-5} cm^2/sec.

When the current-time curves are studied in Figure 43, it will be seen that they are all separated from one another within the first 10 seconds of diffusion even for the thickest films (50 and 5 mm), where the air interface would be too far away from the electrode to interfere with the diffusion boundary. Theoretically the curves for the 50 and 5 mm films should not start separating until the boundary has moved at least 3 to 4 mm from the electrode, which according to Figure 44 occurs after about 250 seconds time. That this is not the case must be due to other factors such as vibrations and convection interfering with the diffusion boundary.

In order to study the relationship that exists between ODC and film thickness, the ODC value recorded at 2 minutes time by each current-time curve was extracted from Figure 43. Since theoretically (according to Fick's first law of diffusion) the ODC value should be inversely proportional to film thickness, the values taken from Figure 43 were plotted against the reciprocal of the film thickness, see Figure 45. From this it is seen that a minimum ODC value is produced at a film thickness of 2 mm and that for films both thicker and thinner than this the ODC increases. The reason for the increase of ODC as the film exceeds 2 mm in thickness is probably due to increased movement of the liquid as the meniscus is raised further above the electrode. Thus, vibrations occurring in the temperature room as well as any convection movement that might arise through temperature or density differences set up in the diffusion chamber would be more active in the thicker layers, where the diffusion boundary only extends over part of the film and leaves an upper unaffected portion to move down and interfere with its movement. When the film exceeded 10 mm in thickness the ODC remained constant, indicating that maximum inner movement of the liquid was reached. Although attempts were made to prevent inner movement of the liquid in the thicker films, these were not successful due mainly to the large diameter of the tube and the small vibrations that were always present in the laboratory.

When the films decreased in thickness below 2 mm, the ODC increased in value essentially in proportion to the reciprocal of the film thickness as the straight line shows in Figure 45. The deviations obtained depend to a large extent on the difficulties involved in accurately measuring the thickness of the films and of preventing inner movement of the liquid. The diffusion process is also affected by the proportionally greater effects caused by the air-liquid and liquid-platinum interfaces as the film decreases in thickness. Thus as the film decreases in thickness its structure will also change considerably due to the greater influence of the boundary or interface layers.

The highest ODC value recorded was 250 microamperes, which was obtained for the thinnest film that could be maintained across the platinum electrode surface. Two current-time curves obtained for such films are shown in Figure 46, where the curve for a 50 mm thick film is shown for comparison. Curve 1 in this figure reaches a maximum of 240 microamperes after 12 minutes and then begins to decrease due to breakage of the film, while curve 2 reaches a maximum of 225 microamps after 6 minutes, where it then breaks and therefore begins to decrease in value.

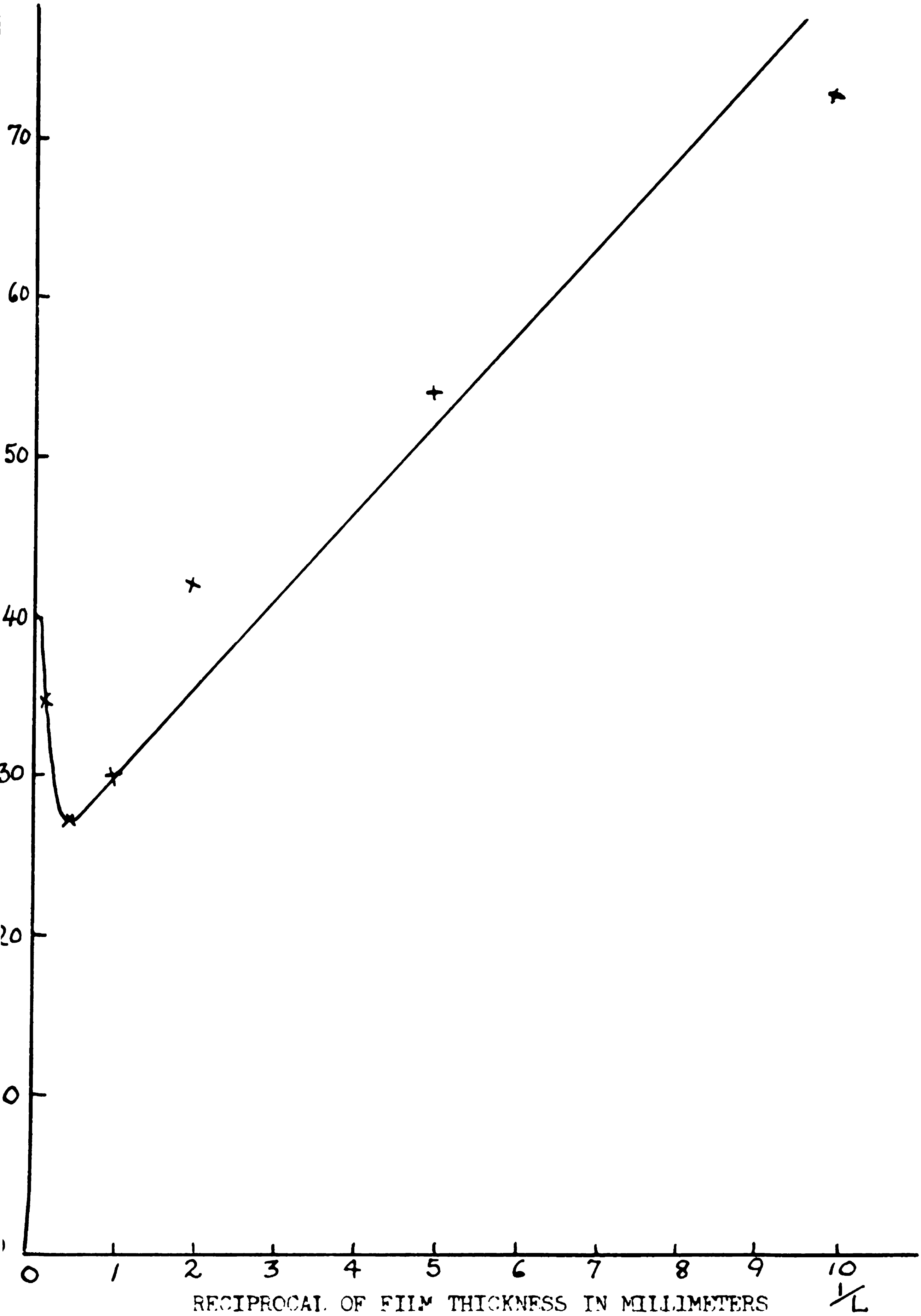


Figure 45. Two minute ODC values from Figure 43 plotted against reciprocal of film thickness.

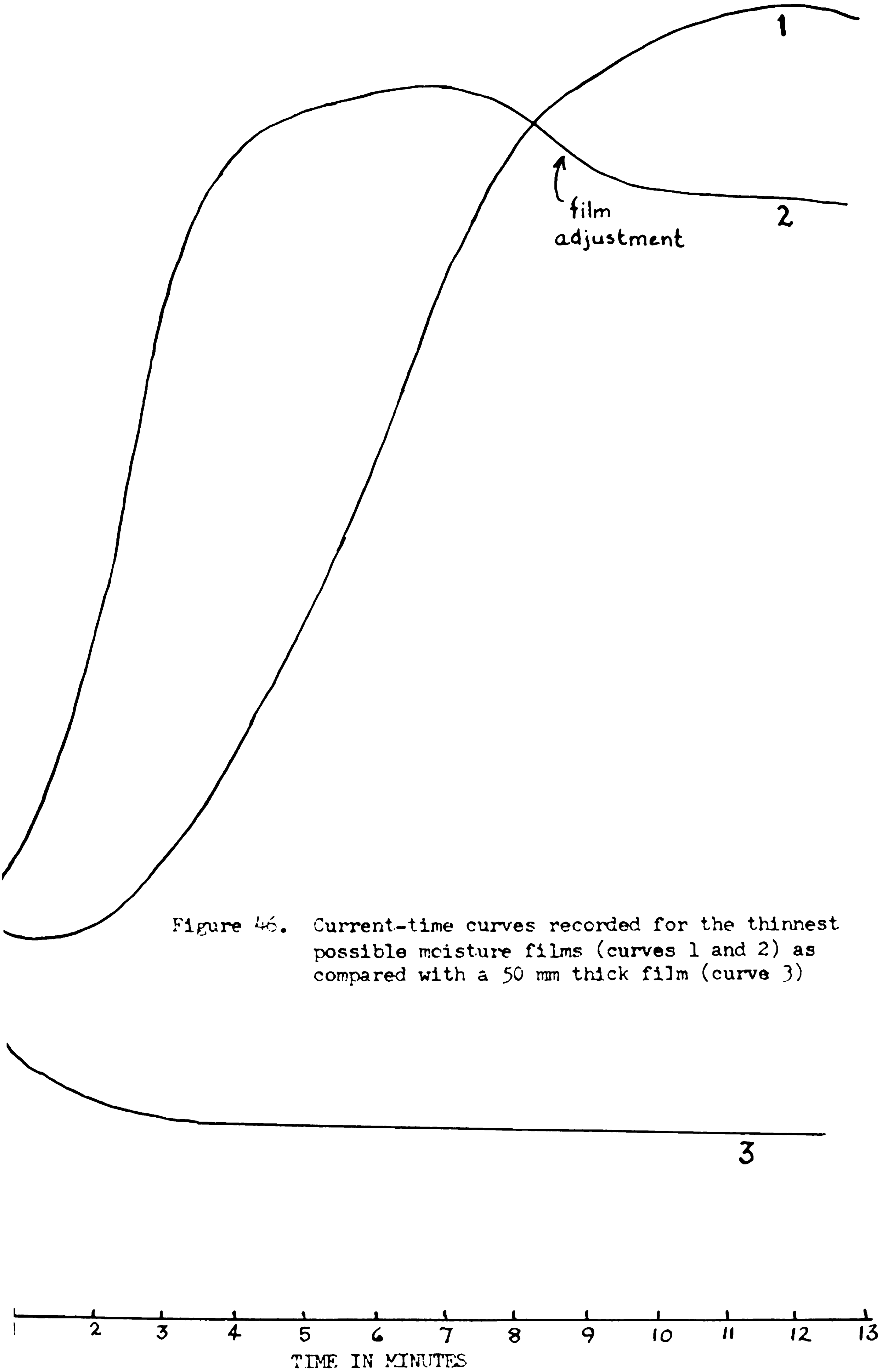


Figure 46. Current-time curves recorded for the thinnest possible moisture films (curves 1 and 2) as compared with a 50 mm thick film (curve 3)

2. A Study of ODR Through Moisture Saturated Media

Having studied in the first section diffusion of oxygen through a liquid phase system (aqueous) as well as through a combined liquid and gaseous phase system (the air-water interface), the next step was to study diffusion in systems containing also a solid phase. Current-time curves were recorded for 50 mm thick layers of various porous materials that were completely saturated with 0.5N KCl solution. Four different size fractions of glass beads as well as several soil materials were used. The current-time curves obtained are shown in Figure 47.

For the purpose of comparison, the current-time curve for KCl solution alone is also included in Figure 47. It will be noticed that this (curve 1) lies well above the curves recorded for the saturated solid materials. The shapes of all the curves recorded in this figure are otherwise essentially the same and at the end of about 3 minutes they all approach fairly constant ODC values. This means that the diffusion process taking place is not linear. For a linear process the product $i\sqrt{t}$ should be a constant (see equation 37), which is not the case here as shown in Table 3. Vibrations from the outside which cause movement of the liquid phase could be one reason for this. Another could be that the reaction products formed from the reduction of oxygen, establish density differences at the electrode surface which in turn caused convection. To test the latter effect current-time curves were run on the same materials with the electrode and diffusion chamber inverted. The open end of the diffusion chamber was closed with a rubber stopper. No changes in the curves were observed. It was therefore concluded that vibrations occurring in the temperature room were the cause to the

TABLE 3

AN ANALYSIS OF THREE ODC-TIME CURVES TAKEN FROM FIGURE 47 SHOWING THE CHANGE IN THE ODC (i) AND PRODUCT $i\sqrt{t}$ WITH TIME

Film Thickness		Time t in seconds 15	30	60	90	120	180
KCl solution							
	ODC (i)	--	--	42.5	38.0	34.5	32.2
	$i\sqrt{t}$	--	--	319	360	378	432
Large beads							
	ODC (i)	--	--	37.0	30.8	27.0	24.0
	$i\sqrt{t}$	--	--	286	292	295	322
Conover loam							
	ODC (i)	48.5	30.0	21.7	18.8	17.1	15.6
	$i\sqrt{t}$	188	164	168	178	187	209

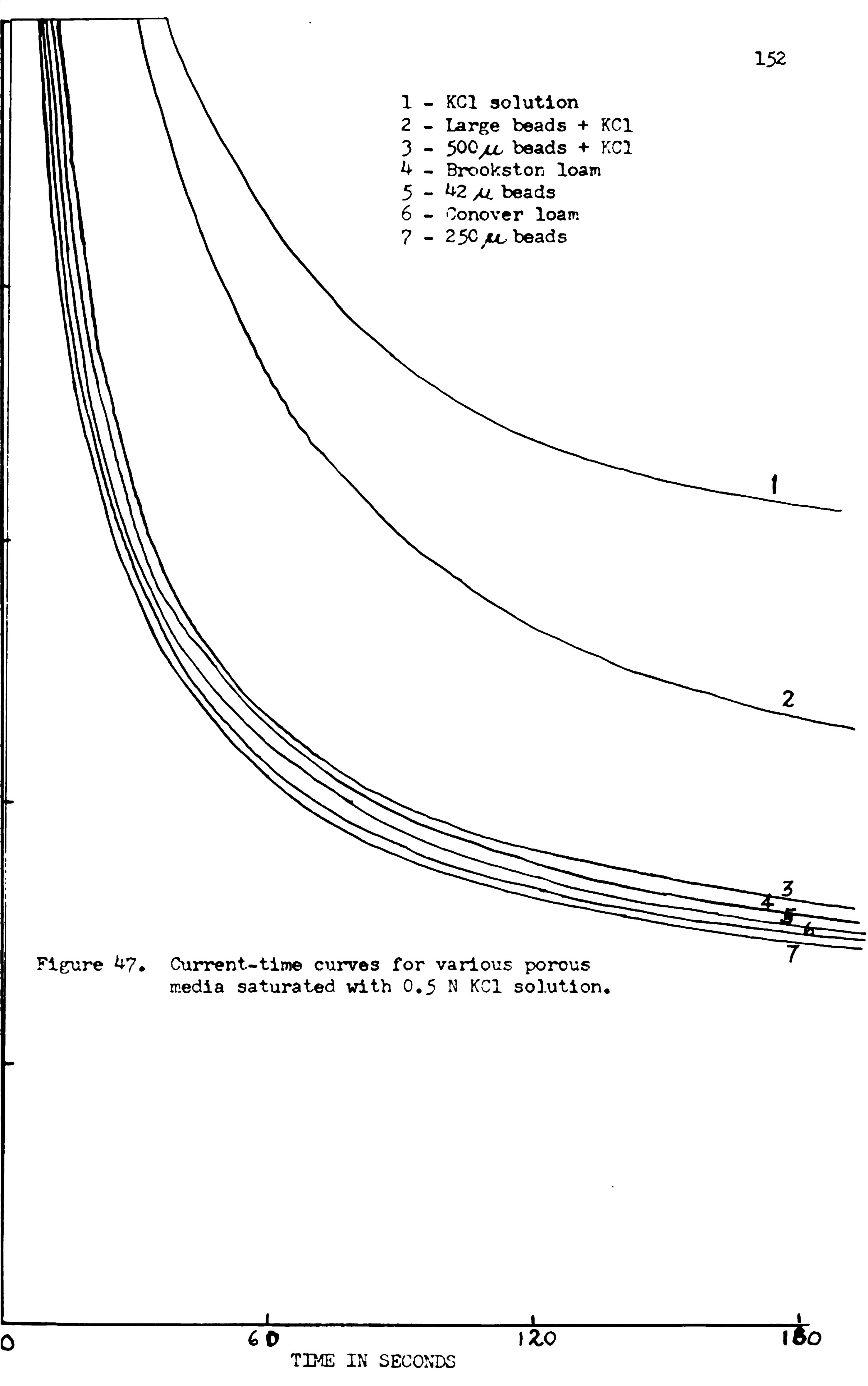


Figure 47. Current-time curves for various porous media saturated with 0.5 N KCl solution.

disturbance of the linear diffusion process. The large width of the diffusion chamber (12.7 mm), also facilitated liquid movement. A narrower tube could hardly be used, however, since this would restrict adequate volumes of porous materials from being used.

Since the diffusion process through the saturated media studied here was not linear, equation (38) could not be applied either for a determination of the effective diffusivity D_e of oxygen through the media.

Figure 47 shows how the introduction of a solid phase into the KCl solution considerably reduced the ODC measured with the electrode. When large glass beads 4.5 mm in diameter were put into the solution, and stacked as a 50 mm layer above the electrode, the ODC at the end of 3 minutes was reduced from 31 to 22 microamperes. Only 4 beads rested against the electrode and the volume relationship between beads and solution was very nearly 1:1 (i.e. porosity of 0.49). When smaller beads and soil materials were used this relationship changed to about 2:1 (i.e. porosity varied between 0.30-0.37). The current-time curves for these finer materials were also lower and very much alike. Several measurements showed there was no consistent order to the relative positions of these curves; the manner in which the material was packed into the diffusion chamber seemed to be of more importance. Loose packing gave slightly higher current values than the more condensed packing. Of course the porosities of these materials was very similar which could account for the similarity of the curves.

That there should be a relationship between porosity and ODC seems fairly evident. It was also found that by adding one, two, three, and four of the large beads to the chamber filled with KCl solution, that current-time curves were obtained that ranged between the pure KCl solution curve (curve 1) and the curve for the large beads filling the chamber (curve 2). Also the curve for just the four beads in chamber was essentially identical with that for the chamber filled with these beads, showing that the diffusion boundary never exceeded the first layer of beads.

The reasons for the reduction in ODC as solid materials were added to the liquid phase are probably several. One effect of the solid material is to dilute the amount of oxygen dissolved in the system, since it does not in itself contain any dissolved oxygen. Another effect is that the solids block the diffusion of oxygen to the electrode, so that the cross-sectional area available for diffusion is reduced. Furthermore the pathway to the electrode will become longer due to the increased tortuosity of the liquid medium as the porosity of the solid material decreases. There should therefore be a relationship existing between ODC and porosity of the solid material. When ODC values recorded for various materials at the end of 5 minutes were taken and compared with the corresponding porosity of the material, Table 4 and Figure 48 were obtained. These give evidence that there is a direct relationship between these variables. However, since other factors, such as method of packing the material in the tube and difficulties in exactly determining the porosity of the material are involved the exact nature of the relationship cannot here be evaluated.

TABLE 4

COMPARISON OF 5 MINUTE ODC VALUES AND CORRESPONDING POROSITY OF SATURATED POROUS MEDIA

Material	Porosity	ODC in μ amps
KCl solution	1.0	30.5
3% Bentonite clay suspension	0.98	26.5
1 glass bead	0.87	28.0
2 glass beads	0.75	26.5
3 glass beads	0.62	23.5
4 glass beads	0.50	21.0
500 μ glass beads	0.38	15.0
250 μ glass beads	0.35	13.3
42 μ glass beads	0.41	13.5

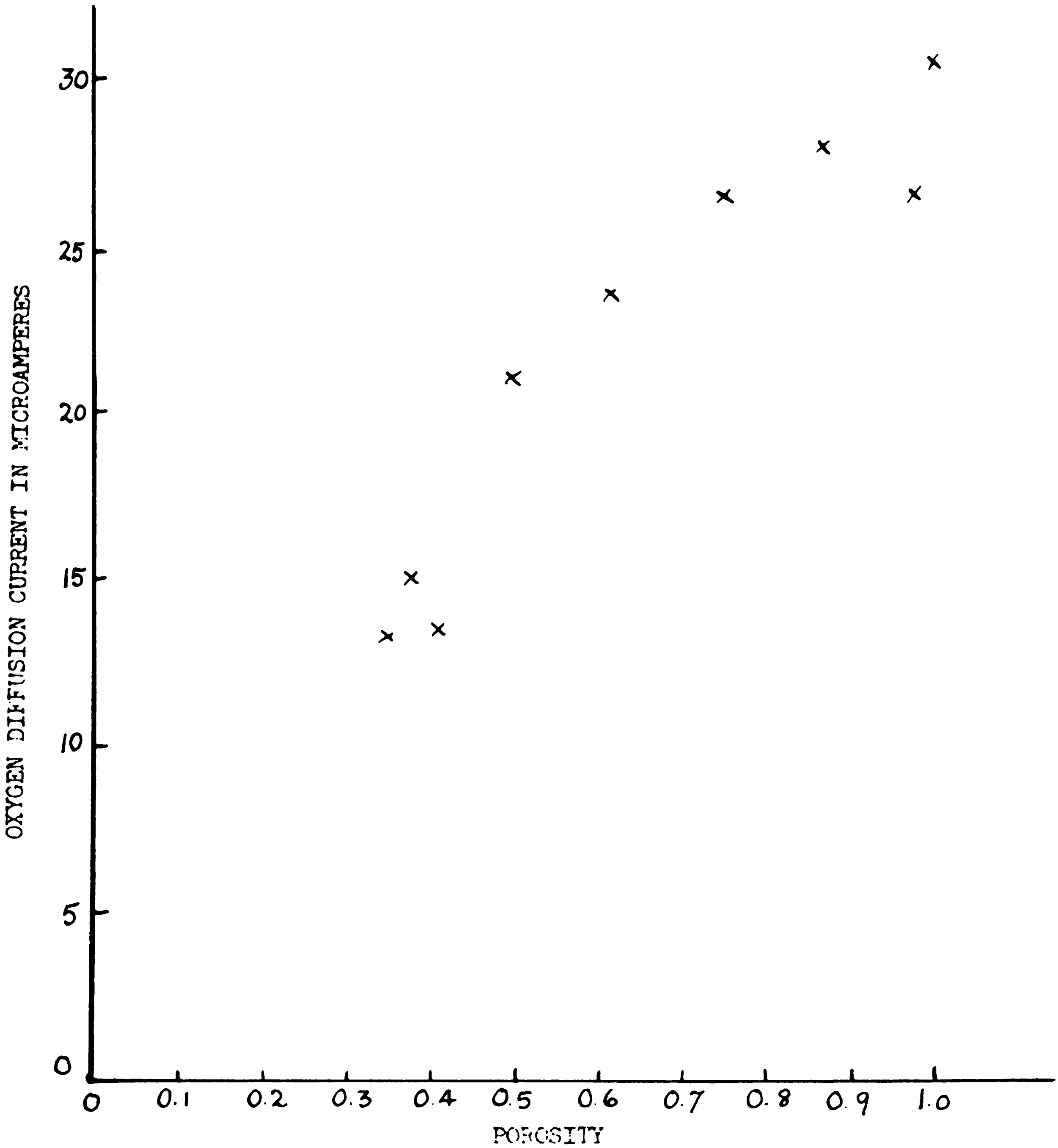


Figure 48. Relationship between 5 minute ODC value and porosity of saturated material.

3. A Study of ODR Through Porous Media of Varying Moisture Content

Diffusion of oxygen through porous systems consisting of three phases--solid, liquid and gaseous--was the next condition to be studied. The diffusion chamber was filled with the same porous materials as studied in section 2 and current-time curves were recorded for different moisture tensions applied. The moisture range between complete saturation of the material to the moisture content at which the film across the electrode was broken was divided into 5 or 6 stages. Current-time curves were recorded for each of these. Tensions up to 60 cm were applied by means of the burette, which was also used to measure the amount of moisture extracted from the material for each tension applied. Figure 49 shows the series of curves that were obtained for a system composed of large glass beads (4.5 mm diameter). The glass beads were stacked in the diffusion chamber so that only 4 beads rested on the electrode and the porosity of the material as a whole was about 0.50.

In Figure 49 curves 1, 2, 3, and 4 correspond to tensions of 0, 20, 40 and 50 mm respectively measured from the surface of the material, which was 50 mm above the electrode surface. As can be seen there is no significant difference between these curves. The air-liquid interface could be seen through the transparent wall of the diffusion chamber and was still about 3 mm from the electrode surface at 50 mm tension. When 53 mm tension was applied, this interface was brought to within 1 mm of the electrode surface and curve 5 was recorded. As Figure 49 shows this gave ODC values which were more than twice the values recorded by the previous curves. After this only a millimeters change in tension brought about large increases in ODC produced, as curves 6-8 will show.

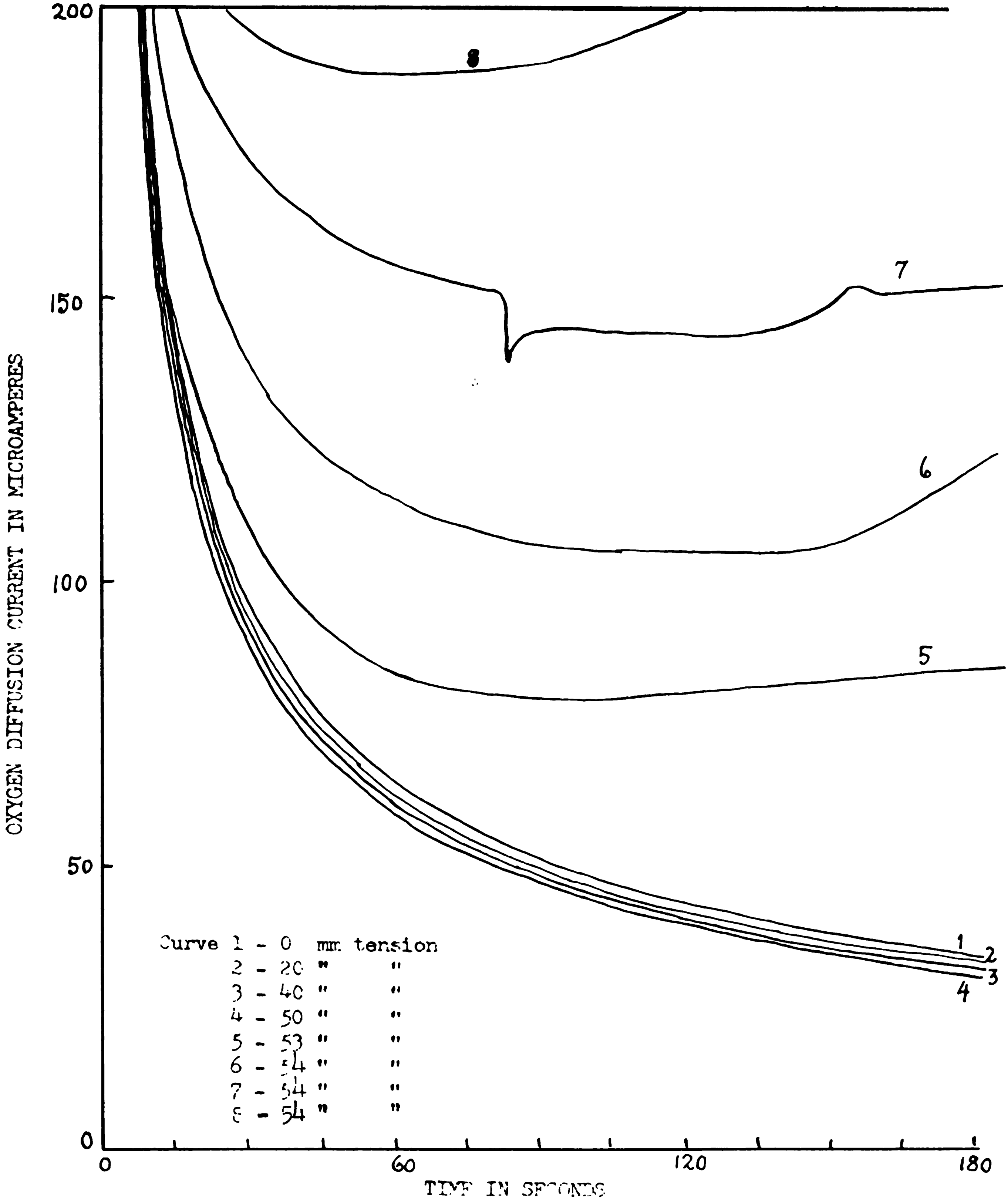


Figure 49. Current-time curves for 4.5 mm glass beads under different moisture tensions.

These curves are irregular due to rearrangements of the moisture films around the electrode. The sudden decrease in ODC shown in curve 7 is due to a sudden thickening of the moisture layer above the electrode while the increase shown by curve 6 is due to a decrease of the same. When 56 mm tension was exceeded, the moisture film over the electrode broke, so that no more oxygen reduction could take place.

The current-time curves recorded for the other materials under various moisture tensions were of exactly the same type as those shown for the large glass beads in Figure 49. No changes occurred in the curves until an air-liquid interface was brought to the surface of the electrode. After this the electrode became extremely sensitive to any changes that occurred over a rather limited range. The curves were usually very irregular and non-reproducible. It therefore seems as if the apparatus used here is only suitable for studying changes occurring in the microstructure around the electrode and not for following changes in the bulk of the medium. The importance of the thickness of the moisture layer at the electrode surface was, however, nicely illustrated. It is also interesting to note that the maximum ODC values obtained for these studies were 200-250 microamperes which was as high as that obtained for a moisture film alone.

D. Summary of Laboratory Studies

The electrolytic reduction of oxygen at the surface of a platinum electrode was used to study the oxygen diffusion rate (ODR) through various materials of soil-like nature. The results showed that the thickness of the moisture film covering the electrode surface was the most important factor determining the ODR to the electrode. The ODR and corresponding thickness of moisture film followed closely the inverse relationship predicted by diffusion theory. At high moisture contents, where the film thickness was too great to have any influence, the porosity of the soil material became an important factor. Thus ODR was found to be directly proportional to porosity under these high moisture conditions.

Although the ODR studies were made in a vessel especially designed to give linear diffusion, the current-time curves showed that such conditions did not prevail. The diffusion zone that developed at the electrode surface and which moved outwards as diffusion continued was not linear due to disturbances through inner movement of the liquid medium. Thus Fick's law of diffusion could not be applied for a determination of the true diffusion coefficients from the current-time curves recorded for various media.

CHAPTER V

SUMMARY

The purpose of this investigation has been to study the hanges that take place in the aeration conditions of a soil as it ndergoes drainage.

In the past both practical and theoretical work on drainage as been mainly concerned with the engineering aspects of the removal f water from the soil and land. Very little attention indeed has been iven to the aeration aspects, although these are of greatest significance plant growth. Thus, rather vague conceptions exist at present as to w drainage actually improves the soil environment for the plant roots d what really constitutes the ideal drainage condition, for which e should strive.

A review of the literature on soil aeration showed that the ration process could be considered as composed of two phases--one volving the diffusion of oxygen through the gas-filled pores of the il and the other consisting of the diffusion of oxygen through the isture films around the plant root. In the surface soil the closeness the atmosphere will generally guarantee a rapid diffusion of oxygen rough the gas phase, so that this will not be limiting to plant

growth and the concentration of oxygen in this will always be maintained at about the same level as in the atmosphere. The diffusion of oxygen through the moisture film around the root is, however, a very slow process and depending on its thickness can be a serious limitation to the supply of oxygen to the plant roots.

The platinum microelectrode is an instrument which can be inserted in the soil and there made to act as an oxygen absorber very similar to a plant root. It gives a measure of the oxygen diffusion rate (ODR) through the moisture film that surrounds it. This ODR value will be closely related to the rate at which oxygen diffuses to a plant root, living in the same environment.

By using the platinum microelectrode technique and limiting the measurements to the surface soil (4 inch depth), it was found possible in this investigation to receive very valuable information regarding the effects of drainage on the aeration conditions of the soil. Measurements of the ODR and moisture content were made perpendicular to the drainage facility (tile line in the case of tile drainage and bed ridge in the case of bedding) at five different locations, four of which were situated in Michigan and one in northern Ohio. As far as possible the complete drainage process was followed by continuing these measurements over a long period of time.

Laboratory studies were also carried out to measure the ODR through various idealized soil systems in order to learn more about the factors that affect the diffusion of oxygen through the liquid phase. A special oxygen diffusion chamber was used which made it possible to regulate the moisture conditions as desired.

The results of the field and laboratory studies may be ummarized as follows:

a) The thickness of the moisture film which covers the surface f the platinum microelectrode (or plant root which it simulates) is the ost important factor governing the oxygen diffusion rate (ODR) to the lectrode (or root). The laboratory studies showed that as the film hickness decreased below 1 mm, the ODR increased logarithmically until stage was reached when the film became so thin that it would break part. For film thicknesses exceeding 1 mm the ODR was rather low and lmost independent of film thickness.

b) Drainage affects the ODR measured with the platinum micro- lectrode by removing water from the soil and thereby decreasing the hickness of the moisture film that covers its surface. If this film hickness could be accurately measured it would be one of the best soil roperties with which to characterize drainage and its effects on soil ration. A value can be estimated from the ODR by making certain ssumptions. This estimated value has been called the "apparent diffusion th length." To calculate it, a knowledge of the diffusion coefficient oxygen through the soil medium surrounding the electrode is necessary, wever, and this is difficult to measure.

c) Besides the thickness of the moisture film layer around e electrode, its porosity will also affect the ODR by determining the oss-sectional area available for oxygen diffusion to the electrode. is factor is of greatest importance when the moisture film is thick. r saturated conditions the laboratory studies showed a very direct and ear relationship between ODR and porosity. As the soil is drained and the moisture films decrease in thickness, the ODR becomes so great that the porosity essentially loses significance.

d) Tile drainage will increase the ODR of the surface soil in proportion to the lateral distance of the soil to the tile. Weather and soil conditions modify these effects, but for given conditions the relation between ODR and lateral distance to the tile could be used as a basis for determining the most appropriate spacing of the tiles.

e) Tile drainage is superior to surface drainage because of its effects in accelerating water seepage from the surface soil to the underlying subsoil, thereby preventing undue saturation and clogging of the pore spaces of the surface soil. This will reduce the periods of oxygen deficiency and thereby lessen the injury to plants.

f) Surface drainage is superior to no drainage because when the soil is ponded with water, oxygen diffusion from the atmosphere to the soil will be completely stopped and thereby prevent any but the aquatic plants from growing there. In this investigation surface water was found to remain for time periods of days and even weeks on undrained land at certain of the locations studied.

g) A continuous measure of the ODR and moisture status of the soil under field conditions will make possible a registration of the periods over which the soil will be deficient in oxygen or water. It will also give a good measure of the effects of various drainage systems in keeping the soil under optimum conditions for the development of the plant roots. This should be used to a greater extent in evaluating and designing drainage treatments.

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APPENDIX

TABLE A

OXYGEN DIFFUSION RATES (ODR) AND SOIL MOISTURE
CONTENTS (MC) MEASURED BETWEEN TWO TILE
LINES AT STATION I, SOIL SCIENCE FARM

<table>
<tr><th rowspan="3">Date
1960</th><th rowspan="3"></th><th colspan="6">Distance in Feet From</th><th rowspan="3">Average values</th><th rowspan="3">Temp. °F.</th></tr>
<tr><th colspan="3">East tile</th><th colspan="3">West tile</th></tr>
<tr><th>0-2</th><th>5-10</th><th>15-20</th><th>15-20</th><th>5-10</th><th>0-2</th></tr>
<tr><td colspan="10"><u>First Period</u></td></tr>
<tr><td>April 12 a.m.</td><td>ODR</td><td>0.6</td><td>0.6</td><td>1.2</td><td>1.8</td><td>1.2</td><td>1.2</td><td>1.0</td><td>44</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">1.5</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td></td><td></td><td colspan="2">not determined</td><td></td><td></td><td></td><td></td></tr>
<tr><td>p.m.</td><td>ODR</td><td>1.8</td><td>2.4</td><td>1.8</td><td>1.8</td><td>3.0</td><td>1.8</td><td>2.2</td><td>60</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">1.8</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td></td><td></td><td colspan="2">not determined</td><td></td><td></td><td></td><td></td></tr>
<tr><td>April 13</td><td>ODR</td><td>9.6</td><td>6.6</td><td>4.2</td><td>3.0</td><td>5.4</td><td>3.6</td><td>5.8</td><td>52</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">3.6</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td></td><td></td><td colspan="2">not determined</td><td></td><td></td><td></td><td></td></tr>
<tr><td>April 19</td><td>ODR</td><td>15.0</td><td>13.8</td><td>15.0</td><td>6.6</td><td>9.0</td><td>4.8</td><td>10.7</td><td>45</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">10.8</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td></td><td></td><td colspan="2">not determined</td><td></td><td></td><td></td><td></td></tr>
<tr><td>April 21</td><td>ODR</td><td>29.4</td><td>33.0</td><td>29.4</td><td>39.6</td><td>39.6</td><td>31.2</td><td>33.5</td><td>65</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">34.5</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td>23.8</td><td>24.2</td><td>24.5</td><td>23.0</td><td>22.6</td><td>24.6</td><td>23.8</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">23.8</td><td></td><td></td><td></td><td></td></tr>
<tr><td>April 22</td><td>ODR</td><td>43.2</td><td>44.4</td><td>44.4</td><td>49.8</td><td>57.6</td><td>54.0</td><td>49.3</td><td>72</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">47.1</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td>19.7</td><td>20.9</td><td>19.4</td><td>19.9</td><td>19.3</td><td>21.1</td><td>20.1</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">19.7</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="10"><u>Second Period</u></td></tr>
<tr><td>April 26</td><td>ODR</td><td>22.2</td><td>21.0</td><td>19.2</td><td>16.2</td><td>19.2</td><td>18.6</td><td>19.7</td><td>54</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">17.7</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td>24.7</td><td>24.8</td><td>24.7</td><td>25.6</td><td>24.7</td><td>22.7</td><td>24.5</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">25.2</td><td></td><td></td><td></td><td></td></tr>
<tr><td>April 29</td><td>ODR</td><td>49.8</td><td>47.4</td><td>43.2</td><td>40.8</td><td>47.4</td><td>52.2</td><td>47.8</td><td>54</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">42.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>MC</td><td>16.7</td><td>17.2</td><td>17.0</td><td>18.1</td><td>17.9</td><td>16.6</td><td>17.4</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">17.6</td><td></td><td></td><td></td><td></td></tr>
</table>

ODR values are expressed in 10^{-8} gm O_2 cm^{-2} min^{-1}
MC values are expressed in percent by weight of dry soil

TABLE B

OXYGEN DIFFUSION RATES (ODR) AND SOIL MOISTURE CONTENTS (MC) MEASURED BETWEEN TWO TILE LINES AT STATIONS II AND III, SOIL SCIENCE FARM

Date 1960		Distance in Feet From East tile 0-2	East tile 5-10	East tile 15-20	West tile 15-20	West tile 5-10	West tile 0-2	Average values	Temp. °F.
Station II									
April 13	ODR	22.8	14.4	14.4	16.2	16.8	24.6	18.8	59
				15.3					
	MC			not determined					
April 19	ODR	24.0	24.6	19.2	15.0	24.0	27.0	23.3	59
				17.1					
	MC	19.8	23.3	24.5	22.8	23.0	20.1	22.3	
				23.7					
Station III									
April 22	ODR	52.2	43.8	43.2	48.0	52.8	57.6	50.4	70
				45.6					
	MC	13.9	14.2	14.6	14.4	14.5	13.5	14.2	
				14.5					
May 5	ODR	66.0	58.8	55.2	57.6	54.6	65.4	60.2	69
				56.4					
	MC	12.8	13.6	13.5	12.6	12.0	11.2	12.6	
				13.1					

ODR values are expressed in 10^{-8} gm O_2 cm^{-2} min^{-1}

MC values are expressed in percent by weight of dry soil

TABLE C

OXYGEN DIFFUSION RATES (ODR) AND SOIL MOISTURE CONTENTS (MC) MEASURED ACROSS A TILE LINE AT FARM CROPS FARM

<table>
<tr><th rowspan="3">Date
1960</th><th rowspan="3"></th><th colspan="6">Distance From Tile in Feet</th><th rowspan="3">Average values</th><th rowspan="3">Temp. °F.</th></tr>
<tr><th colspan="3">South</th><th colspan="3">North</th></tr>
<tr><th>15-20</th><th>5-10</th><th>0-2</th><th>0-2</th><th>5-10</th><th>15-20</th></tr>
<tr><td rowspan="2">April 22</td><td rowspan="2">ODR</td><td rowspan="2">22.8</td><td rowspan="2">27.0</td><td>34.2</td><td>41.4</td><td rowspan="2">33.0</td><td rowspan="2">27.0</td><td rowspan="2">29.5</td><td rowspan="2">56</td></tr>
<tr><td colspan="2">37.8</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">MC</td><td rowspan="2">25.1</td><td rowspan="2">23.2</td><td>19.7</td><td>16.3</td><td rowspan="2">22.6</td><td rowspan="2">26.2</td><td rowspan="2">23.0</td><td rowspan="2"></td></tr>
<tr><td colspan="2">18.0</td></tr>
<tr><td rowspan="2">April 26</td><td rowspan="2">ODR</td><td rowspan="2">26.4</td><td rowspan="2">29.4</td><td>31.8</td><td>35.4</td><td rowspan="2">27.6</td><td rowspan="2">22.2</td><td rowspan="2">27.8</td><td rowspan="2">53</td></tr>
<tr><td colspan="2">33.6</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">MC</td><td rowspan="2">24.6</td><td rowspan="2">23.0</td><td>18.8</td><td>-</td><td rowspan="2">22.2</td><td rowspan="2">24.6</td><td rowspan="2">22.8</td><td rowspan="2"></td></tr>
<tr><td colspan="2">18.8</td></tr>
<tr><td rowspan="2">April 28</td><td rowspan="2">ODR</td><td rowspan="2">26.4</td><td rowspan="2">31.8</td><td>40.2</td><td>40.4</td><td rowspan="2">33.0</td><td rowspan="2">29.4</td><td rowspan="2">32.2</td><td rowspan="2">49</td></tr>
<tr><td colspan="2">40.3</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">MC</td><td rowspan="2">20.3</td><td rowspan="2">21.4</td><td>15.7</td><td>18.8</td><td rowspan="2">20.9</td><td rowspan="2">21.8</td><td rowspan="2">19.8</td><td rowspan="2"></td></tr>
<tr><td colspan="2">17.3</td></tr>
<tr><td rowspan="2">May 5</td><td rowspan="2">ODR</td><td rowspan="2">42.6</td><td rowspan="2">49.2</td><td>57.6</td><td>56.4</td><td rowspan="2">49.2</td><td rowspan="2">48.0</td><td rowspan="2">49.2</td><td rowspan="2">69</td></tr>
<tr><td colspan="2">57.0</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">MC</td><td rowspan="2">20.0</td><td rowspan="2">14.9</td><td>13.8</td><td>13.5</td><td rowspan="2">14.5</td><td rowspan="2">14.5</td><td rowspan="2">15.5</td><td rowspan="2"></td></tr>
<tr><td colspan="2">13.7</td></tr>
</table>

ODR values are expressed in 10^{-8} gm O_2 cm^{-2} min^{-1}

MC values are expressed in percent by weight of dry soil

TABLE D

OXYGEN DIFFUSION RATES (ODR) AND SOIL MOISTURE CONTENTS (MC) MEASURED ACROSS A TILE LINE ON DIFFERENT PLOTS AT FERDEN FARM

Location and date 1960		Distance From Tile in Feet West 15-20	5-10	0-2		East 0-2	5-10	15-20	Average value	Temp. °F.
April 25										
Plot 6	ODR	23.4	25.8	31.8		27.0	27.0	24.6	26.0	45
					29.4					
	MC	28.2	27.5	27.7		27.5	27.8	26.2	27.5	
					27.6					
Plot 5	ODR	12.0	16.2	22.8		23.4	24.6	14.4	18.1	55
					23.1					
	MC	30.5	30.0	28.7		28.8	29.4	30.0	29.7	
					28.8					
Plot 3	ODR	32.4	34.8	37.2		33.6	29.4	-	33.0	52
					35.4					
	MC	29.7	27.4	28.9		28.3	30.4	-	29.0	
					28.6					
April 26										
Plot 5	ODR	23.4	29.4	26.4		33.6	30.0	22.2	27.0	53
					30.0					
	MC	29.9	29.5	29.3		29.7	29.7	30.6	29.8	
					29.5					
Plot 1	ODR	26.4	30.0	31.8		30.0	29.4	26.4	28.6	52
					30.9					
	MC	28.9	27.0	30.2		29.8	29.5	30.6	29.2	
					30.0					
April 27										
Plot 3	ODR	40.2	39.0	43.2		43.8	40.2	40.2	40.6	60
					43.5					
	MC	26.0	25.0	25.9		25.6	27.2	24.2	25.6	
					25.8					
Plot 1	ODR	32.4	33.0	34.2		32.4	33.0	32.4	32.8	53
					33.3					
	MC	30.0	29.1	28.2		28.2	28.7	29.2	28.9	
					28.2					

TABLE D (CONTINUED)

Location and date 1960		West 15-20	West 5-10	West 0-2	East 0-2	East 5-10	East 15-20	Average value	Temp. °F.
April 28									
Plot 6	ODR	39.0	40.2	38.4	41.4	39.6	34.2	38.6	64
				39.9					
	MC	23.3	25.4	23.5	23.5	22.5	23.2	23.5	
				23.5					
Plot 5	ODR	32.4	33.0	39.0	33.6	34.2	33.6	33.9	60
				36.3					
	MC	24.2	24.0	24.9	23.9	24.2	25.3	24.4	
				24.4					
May 4									
Plot 6	ODR	40.2	42.0	43.8	47.4	47.4	45.6	44.2	66
				45.6					
	MC	19.0	19.6	21.7	18.3	18.8	20.5	19.6	
				20.0					
Plot 5	ODR	32.4	38.4	39.0	43.8	42.6	34.8	37.9	67
				41.4					
	MC	24.7	22.5	22.6	23.2	21.0	22.9	22.8	
				22.9					
Plot 1	ODR	34.8	40.2	41.4	37.2	40.8	39.0	38.8	69
				39.3					
	MC	26.9	24.4	25.4	25.8	25.8	26.9	25.9	
				25.6					
Plot 3	ODR	47.4	44.4	44.4	46.2	48.0	43.8	45.8	68
				45.3					
	MC	21.8	20.3	20.9	18.6	19.8	19.3	20.2	
				19.8					
May 10									
Plot 3	ODR	28.2	27.6	28.8	27.0	28.2	31.2	28.6	48
				27.9					
	MC	29.0	29.6	30.3	29.4	29.3	29.4	29.5	
				29.9					

TABLE D (CONTINUED)

Location and date 1960		Distance From Tile in Feet West 15-20	West 5-10	West 0-2		East 0-2	East 5-10	East 15-20	Average value	Temp. °F.
May 12										
Plot 6	ODR	22.2	23.4	22.8	24.9	27.0	21.6	24.6	23.3	47
	MC	29.8	28.9	29.0	29.1	29.1	29.5	27.6	29.0	
Plot 5	ODR	9.0	17.4	17.4	18.0	18.6	13.2	16.8	14.9	47
	MC	29.9	29.7	29.7	29.2	28.7	29.3	29.6	29.5	
Plot 1	ODR	21.0	22.2	25.2	25.5	25.8	26.4	25.2	24.1	47
	MC	29.8	29.3	29.2	29.1	29.0	30.5	30.7	29.9	
Plot 3	ODR	27.6	27.0	27.0	28.8	30.6	30.6	28.2	28.4	47
	MC	29.5	31.0	29.4	28.9	28.3	28.9	29.8	29.5	
May 13										
Plot 6	ODR	19.8	20.4	22.8	26.1	29.4	27.6	27.6	24.3	49
	MC				not determined					
Plot 5	ODR	16.8	12.0	16.2	18.0	19.8	17.4	21.0	17.0	49
	MC				not determined					
May 15										
Plot 1	ODR	22.8	33.6	31.2	33.3	35.4	31.8	30.0	30.3	61
	MC	28.8	26.2	26.5	26.1	25.6	30.5	27.1	27.5	
Plot 3	ODR	36.6	36.6	33.0	29.7	26.4	39.0	36.0	35.6	69
	MC	24.1	24.0	24.1	23.5	22.9	23.4	23.2	23.6	

TABLE D (CONTINUED)

Location and date 1960		Distance From Tile in Feet West 15-20	5-10	0-2	East 0-2	5-10	15-20	Average value	Temp. °F.
May 16									
Plot 6	ODR	31.8	31.2	34.8	37.2	35.4	36.0	34.1	68
				36.0					
	MC	22.4	23.8	22.6	24.1	23.3	22.7	23.2	
				23.4					
Plot 5	ODR	28.2	30.0	33.6	32.4	33.6	34.2	31.8	64
				33.0					
	MC	26.7	26.7	26.5	25.9	26.5	26.4	26.5	
				26.2					

ODR values measured in 10^{-8} gm O_2 cm^{-2} min^{-1}

MC values measured in percent by weight of dry soil

TABLE E

MEASUREMENTS OF THE LEVEL OF THE WATER TABLE ON PLOTS 1 AND 6 AT FERDEN FARM DURING SPRING 1960 EXPRESSED AS HEIGHT IN FEET ABOVE THE BOTTOM OF THE TILE (c.f. FIGURE 21)

Location of measurement relative to tile	Date of Measurement									
	April 1960				May 1960					
	25	26	27	28	4	10	12	13	15	16
Plot 6 (Barley stubble)										
20 feet west	0.33	1.00	0.33	--	-0.09	0.50	0.16	0.16	0.08	0.08
10 feet west	--	0.58	0.27	0.10	-0.02	0.48	0.23	0.23	0.15	0.15
Above tile	0.0	0.0	0.0	0.0	-0.09	-0.09	0.08	0.08	0.08	0.08
10 feet east	0.48	1.24	0.76	0.99	0.55	0.66	0.55	0.37	0.33	0.29
20 feet east	0.80	1.64	1.14	1.14	0.39	0.80	0.72	0.59	0.61	0.55
Plot 1 (1st year alfalfa)										
20 feet west							-0.46	-0.46	-0.21	-0.13
10 feet west							0.03	0.12	0.20	0.20
Above tile							0.19	0.10	0.19	0.14
10 feet east							0.20	0.20	0.45	0.45
20 feet east							0.75	0.85	0.75	0.68

TABLE F

OXYGEN DIFFUSION RATES (ODR) AND SOIL MOISTURE CONTENTS (MC) MEASURED ON TILED AND UNTILED LAND AT CRAWFORD FARM MAY 19-20, 1960

Location		Distance From Tile or Bed Ridge in Feet							Average value	Temp. °F
		North				South				
		15-20	5-10	0-2		0-2	5-10	15-20		
Tiled land										
B. Fall plowed	ODR	18.0	27.6	43.2	38.7	34.2	27.6	21.6	26.7	60
	MC	35.4	30.4	27.4	28.7	30.0	33.2	34.8	32.5	
C. 2nd year hay	ODR	24.0	28.2	34.2	32.7	31.2	22.8	17.4	25.0	55
	MC	30.9	25.4	21.5	20.5	19.5	25.8	32.7	27.1	
D. Winter wheat	ODR	21.6	33.6	38.4	38.1	37.8	30.6	21.6	29.1	59
	MC	30.8	28.0	17.5	18.8	20.1	23.1	32.6	26.7	
Untiled land (40 ft. bed)										
B. Fall plowed	ODR	13.8	12.0	13.8	13.8	13.8	16.8	10.2	13.3	59
	MC	25.5	32.1	30.5	30.1	29.6	34.0	36.6	31.7	
C. 2nd year hay	ODR	6.6	12.6	18.6	17.1	15.6	6.6	3.6	9.3	56
	MC	36.3	38.4	37.5	37.3	37.1	36.2	39.1	37.5	
D. Winter wheat	ODR	6.6	14.4	15.0	12.9	10.8	14.4	4.8	10.6	55
	MC	37.4	36.3	36.7	38.6	40.4	47.0	39.7	39.8	

TABLE G

YIELDS OF VARIOUS CROPS MEASURED AT THE CHIPPEWA DRAINAGE PROJECT, CRAWFORD FARM, 1953-1958, ON TILED AND BEDDED LAND. (TAKEN FROM KING ET AL. 1959).

Crops	Sub-plots: Distances in feet from tile or bed ridge	Tiled land: Sub-plot yields	Tiled land: Average	Bedded land: Sub-plot yields	Bedded land: Average
Winter wheat (yields in bush/acre)	0-8	51.2		34.2	
	8-16	50.0	47.7	35.8	31.1
	16-20	41.9		23.3	
Oats (yields in bush/acre)	0-8	71.8		63.5	
	8-16	70.0	68.8	58.5	49.3
	16-20	65.0		30.6	
First year hay (yields in lbs/acre)	0-8	4326		4933	
	8-16	4559	4415	4480	3910
	16-20	4315		2669	
Second year hay (yields in lbs/acre)	0-8	4895		4894	
	8-16	5128	4965	4449	4133
	16-20	4882		3116	

TABLE H

OXYGEN DIFFUSION RATES* MEASURED AT THE TILE SURFACE DRAINAGE EXPERIMENT, OHIO, DURING SEPTEMBER 14-18, 1960

Treatment and replication	Time in hours after irrigation was stopped: 0		25		50		75		100		120	
A. No drainage												
Rep. 1	--	--	--	3.0	4.8	7.4	3.0	4.2	--	4.8	--	3.6
Rep. 2	--	--	7.8	7.4	--	--	--	--	--	--	--	--
Rep. 3	--	--	3.6	3.6	3.6	5.4	3.6	7.2	3.6	4.2	--	--
Rep. 4	11.4	11.4	4.2	5.4	4.8	4.8	--	--	--	--	--	--
Average	11.4		4.8		5.2		4.5		4.2		3.6	
B. Surface drainage												
Rep. 1	--	--	8.4	9.6	12.6	15.0	15.6	16.2	17.4	18.6	22.2	22.8
Rep. 2	--	--	4.8	5.4	--	--	--	--	--	--	--	--
Rep. 3	--	--	4.8	6.6	7.2	8.4	12.0	14.4	17.4	18.6	--	--
Rep. 4	7.2	9.0	3.6	4.2	6.6	9.6	--	--	--	--	--	--
Average	8.1		5.9		9.9		17.1		18.0		22.5	
C. Tile drainage												
Rep. 1	--	--	7.2	7.8	13.8	15.0	17.4	19.8	18.6	20.4	21.6	22.2
Rep. 2	--	--	6.6	7.2	--	--	--	--	--	--	--	--
Rep. 3	--	--	13.8	16.8	12.0	16.2	16.8	20.4	21.0	22.8	--	--
Rep. 4	7.2	7.8	4.2	4.8	9.6	12.0	--	--	--	--	--	--
Average	7.5		8.6		13.1		18.6		20.7		21.9	
D. Surface and tile drainage												
Rep. 1	--	--	15.0	15.6	15.0	17.4	21.0	22.8	23.4	25.2	25.8	28.2
Rep. 2	--	--	9.6	10.2	--	--	--	--	--	--	--	--
Rep. 3	--	--	14.4	17.4	14.4	14.4	19.2	19.2	23.4	24.0	--	--
Rep. 4	9.0	10.2	9.6	11.4	14.4	15.6	--	--	--	--	--	--
Average	9.6		12.9		15.2		20.6		24.0		27.0	

*Values expressed as 10^{-8} gm O_2 cm^{-2} min^{-1}

TABLE I

SOIL MOISTURE CONTENTS IN PERCENT BY WEIGHT OF DRY SOIL MEASURED AT THE TILE-SURFACE DRAINAGE EXPERIMENT, NORTH-CENTRAL SUBSTATION OF OHIO AGRICULTURAL EXPERIMENT STATION DURING SEPTEMBER 14-18, 1960

Treatment and replication	Time in hours after irrigation was stopped											
	0		25		50		75		100		120	
A. No drainage												
Rep. 1-4			Surface water prevailed on all plots									
B. Surface drainage												
Rep. 1	--	--	33.9	33.1	32.8	33.5	31.7	32.1	32.5	33.4	31.9	31.8
Rep. 2	--	--	34.2	36.0	--	--	--	--	--	--	--	--
Rep. 3	--	--	33.2	33.8	34.5	35.1	33.1	35.1	33.2	32.4	--	--
Rep. 4	--	--	34.5	34.6	32.2	33.2	--	--	--	--	--	--
Average	--	--	34.2		33.6		33.0		32.9		31.8	
C. Tile drainage												
Rep. 1	--	--	36.6	33.0	34.9	33.3	31.9	34.1	33.0	33.0	31.5	31.6
Rep. 2	--	--	34.1	35.6	--	--	--	--	--	--	--	--
Rep. 3	--	--	28.9	30.6	31.4	32.1	29.4	29.8	29.1	28.5	--	--
Rep. 4	--	--	(42.2)	33.8	34.2	33.0	--	--	--	--	--	--
Average	--	--	33.3		33.2		31.3		30.9		31.5	
D. Tile and surface drainage												
Rep. 1	--	--	31.1	31.3	32.5	31.4	31.5	32.9	30.7	30.8	30.5	30.8
Rep. 2	--	--	32.2	32.5	--	--	--	--	--	--	--	--
Rep. 3	--	--	32.4	32.0	32.9	32.9	31.2	31.3	31.5	31.2	--	--
Rep. 4	--	--	33.8	34.4	32.5	32.9	--	--	--	--	--	--
Average	--	--	32.5		32.5		31.8		31.1		30.7	

TABLE J

OXYGEN DIFFUSION RATES (ODR) AND SOIL MOISTURE CONTENTS (MC) MEASURED AT THE TILE-SURFACE DRAINAGE EXPERIMENT, NORTH-CENTRAL SUBSTATION OF OHIO AGRICULTURAL EXPERIMENT STATION

Date 1960	Distance From Tile in Feet South 15-20	South 5-10	South 0-2	North 0-2	North 5-10	North 15-20	Average value	Temp. °F.
September 17								
ODR	14.4	15.0	18.6	20.4	16.2	18.0		64
			19.5					
MC	32.3	33.0	32.4		33.0	33.4	32.8	
September 18								
ODR	15.6	18.0	22.2	21.6	17.4	18.6		65
			21.9					
MC	33.1	31.6	30.0		31.5	32.0	31.6	

ODR values expressed in 10^{-8} gm O_2 cm^{-2} min^{-1}

MC values expressed as percent by weight of dry soil

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